CARBON DYNAMICS IN TEAK PLANTED LATERITE SOILS OF KERALA

by

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THESIS

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DECLARATION

I, hereby declare that the thesis entitled **"CARBON DYNAMICS IN TEAK PLANTED LATERITE SOILS OF KERALA"** is a bonafide record of research work done by me during the course of research and the thesis has not been previously formed the basis for the award to me any degree, diploma, fellowship or other similar title, of any other University or Society.

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SYMBOLS AND ABBREVIATIONS

CDM	Clean Development Mechanism
dbh	Diameter at breast height
Ea	Activation energy
FAO	Food and Agriculture Organization
GBH	Girth at breast height
Gt	Giga tonne
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
OC	Organic Carbon
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
UNFCCC	United Nations Framework Convention on Climate Change

CHAPTER 1

INTRODUCTION

Global warming induced climate change has become a serious issue affecting earth systems. Increased concentration of greenhouse gases such as carbon dioxide, methane, nitrous oxide and sulphur hexa fluoride in the earth's atmosphere is one of the most important concerns of humankind today. French scientist Fourier first described greenhouse effect in 1827. The increasing amount of carbon dioxide emission after the industrial revolution have changed the greenhouse gas composition markedly leading to excessive rise in atmospheric temperature.

The greenhouse gases differ in their capacities to increase temperature, which is termed the Global Warming Potential (GWP). Global Warming Potential comparison of CO_2 with methane and nitrous oxide shows that CO_2 is much less harmful than methane and nitrous oxide. However, CO_2 accounts for 64 per cent of the increase in atmospheric heat since it is released in to the atmosphere at enormous levels due to combustion of fuels, especially fossil fuels, the consumption of which has been increasing in geometric proportion in post industrial revolution era (Muslin, 2004). Forest degradation and deforestation together with fossil fuel burning is responsible for this unprecedented increase of carbon dioxide during the last two centuries.

The concentration of CO_2 in the atmosphere has increased from 280 ppm in 1750 to 367 ppm in 1999 and is currently increasing at the rate of 1.5 ppm per year. The 1997 Kyoto Protocol is framed on the principle that CO_2 from the air can be sequestered in the soil and biomass and is a practical way of mitigating climate change. Land use and land management change and forestry activities that are shown to reduce atmospheric carbon dioxide levels are included in the Kyoto emission reduction targets, Article 3.3 of the Kyoto protocol (Van *et al.*, 2003).

Removal of carbon dioxide from atmosphere is achieved through sequestration. Carbon sequestration is the transfer of atmospheric CO_2 into the pools with a longer mean residence time in such a manner that it is not re-emitted to the atmosphere in near future. Forests provide a good option to sequester carbon dioxide from the atmosphere through photosynthesis. This carbon is distributed in the living plants and on death is transformed to carbon, which is stored in the soil. It has been reported that a young forest during its early fast growth period sequester large amount of carbon while an old forest act more as reservoir while adding less carbon annually. Moreover, they can hold large amount of carbon as biomass over long period of decades and even centuries. Among other factors the forests' capacity to sequester carbon varies with species, site, spacing, climate and age.

The world's soils contain about 1550 Pg of organic carbon, which is more than twice the amount in the atmosphere (IPCC, 2007). The soil organic carbon is a complex system consisting of several pools of varying turnover times. Soil organic matter has a dual role in the ecosystem. On the one hand, it positively regulates aggregate stability, cation exchange capacity, nutrient release rate and water holding capacity. The other role of SOM is to store carbon safely for several years. The roles defined for SOM are controlled by two pools – active and passive - and analyzing these pools will give a true sense of the ecosystem sustainability and storage potential.

Different factors prevent the organic matter from biodegradation in soils. The physical and chemical environment has an effect on the stability of the organic carbon in soil. The chemical structure of soil organic matter and its physical accessibility to microbes and enzymes are also important factors regulating organic carbon decomposability. The formation of associations of organic matter and mineral surfaces is considered to be an important process in the soil carbon cycle, as it stabilizes the organic matter in soils against microbial mineralization. Analysing these interactions will provide insight into the ability of soil to store organic carbon and to prevent it from mineralization to CO_2. This will in turn open up vistas for better carbon management in these systems. Devising alternatives/ strategies for long-term carbon management is a very difficult task due to the high vulnerability of the carbon stored in the various systems. To undertake such an activity one has to have a fair idea about the stocks and turnover of soil organic carbon in the various systems over a period.

Kerala is endowed with a rich forest ecosystem and 29 per cent of the landscape is clothed with forests. The natural forests remain largely undisturbed and provide great potential for carbon sequestration. On the other hand, managed forest systems are man-made and besides their natural potential, provides management opportunities to sustain or even improve their carbon capturing and storage potentials.

The managed forest systems in Kerala constitute 1056.02 km^2 (10% of total forest area) and nearly 70 per cent of these are occupied by plantations of teak (*Tectona grandis Linn. f*). Teak has been under planting in Kerala on a plantation scale since 1844, major expansion in area occurred during the period 1960 - 1988 as part of the five year plans. Besides large-scale plantations of Forest Department (~ 75000 ha), farmers have also planted teak across the region, and usually manage their plantations as a complementary crop alongside other land uses within their farms.

In Kerala, teak is raised as a long duration crop with an average duration of 50 – 60 years. Teak is capable of growing over a wide range of edaphic conditions. The studies conducted so far have mainly concentrated on total soil organic carbon content and have not quantified the effects of this continuous teak rotation on the quantity and quality of carbon stored in these soils. Further, mere quantification of the total organic carbon does not indicate the real carbon storage potential of these systems, as only a fraction (passive pools) of this contributes to the actual storage for longer periods. Also there is a need to generate a more comprehensive knowledge about carbon stocks, pools and their thermal sensitivities with teak rotations in order to decide on the choice of this species for continuous rotation and management options vis - a - vis carbon storage.

Carbon sequestration capacity of forest can be supplemented by afforestation of additional land area. The importance of forest in mitigating climate change has prompted countries to maintain carbon budget of their forest resource. It is estimated that during the period 1995-2050 afforestation/reforestation activities can sequester 1.1 to 1.6 Pg per year of which the tropics would contribute 70 per cent (IPCC, 2007).

Soil has greater carbon storage capacity than vegetation and atmosphere giving it a major role in global carbon sequestration. Globally the soil stores 2300 Pg of carbon, which is three times the atmospheric storage, and 3.8 times the storage of biotic pools (Lal, 2002). The upper one meter soil is reported to store twice the amount of atmospheric carbon amounting to 1502 Pg of carbon. Trees contribute to soil organic carbon due to high biomass in above and below ground. Soil carbon is constituted by both organic and inorganic carbon. Organic pool carbon changes by management or land use but inorganic carbon pool lies unaffected due to such reasons. Even a 5per cent increase in organic pool with management techniques can cause a decrease in the atmospheric carbon by up to 16 per cent (Delgado and Follett, 2002).

Wood production along with carbon sequestration makes afforestation and reforestation attractive. Terrestrial vegetation is considered to store around 466 Gt of carbon, 75 per cent of which is in the forest ecosystems mainly in the stems, branches, foliage and roots of trees. Forest soils accounts for 39 per cent of all carbon stored in soils (Bolin and Schroeder, 1997). Long residence time of carbon coupled with high carbon sequestration capacity of forest is receiving greater attention at present. Teak (*Tectona grandis* Linn. F.) is one of the world's high quality timber with durability and appealing colour and hence in great demands in various markets including ship building, furniture and decorative components. It occurs mostly in moist and dry deciduous forest below 1000m elevation. It grows best in hot humid climates with annual rainfall of 1250-3750 mm and temperature of 13-17°C minimum and 39 to 43°C maximum. Teak plantation started in India with first plantation established in Nilambur in the year

1842 and now it is occupying around 75000 ha and is mainly raised in the midland laterites. Teak plantations can sequester carbon from the atmosphere though they do not do so permanently on account of harvested or natural death. An area of 2.4 million ha of teak in the world would have the potential to sequester 240 million tons of carbon.

Teak has been found to sequester carbon more efficiently than most other species. As the teak grows, its height, diameter at breast height (dbh) and biomass increases faster in the initial period. Biomass of tree components also increases with age of the tree, the contribution of different components to the total biomass is highly variable depending on many factors. Carbon sequestration in the biomass follows the same trend, higher the biomass higher the carbon storage. As the teak wood is used for timber purposes, carbon stored in them can be considered to be locked/ sequestered for several years. An effective management approach is to selectively fell mature trees that no more act as sink and plant new ones which can sequester more carbon in its younger years. One hundred and ninety five million tons of carbon was reported to be stored in harvested wood products in the house hold sector and 62 million tons locked in commercial sector. Twenty four million tons of carbon is being locked annually in harvested wood products (FSI, 2013). Hence the present study intend to determine the carbon stocks in managed teak plantations of mid land laterites of Kerala along with analysis of thermal stability of carbon decomposition in aggregates and effect of temperature on carbon dioxide efflux.

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CHAPTER 2

REVIEW OF LITERATURE

Global warming is one of the foremost issues that humans are facing today and a main reason for this warming is excessive accumulation of greenhouse gases, primarily carbon dioxide in the atmosphere (Raceli *et al.*, 2008). Burning of fossil fuel and land use changes emit, increasing quantities of greenhouse gases into the atmosphere. The greenhouse gases mainly include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The greenhouse gases trap the outgoing long wave radiations and causes heating of earth surface, greenhouse effect and ultimately climate change. UNFCCC (2007) pointed out that the main characteristics of climate change are increases in average global temperature, changes in cloud cover, precipitation, melting of ice caps and glaciers and increases in ocean temperatures and ocean acidity, due to seawater absorbing heat and carbon dioxide from the atmosphere.

Over the last century, atmospheric concentrations of carbon dioxide increased from a pre-industrial value of 278 parts per million to 379 parts per million in 2005, and the average global temperature rose by 0.74° C (UNFCCC, 2007). Climate change will have widespread effects on the environment, socio-economic and related sectors, including water resources, agriculture, food security, human health, terrestrial ecosystems, biodiversity and coastal zones (UNFCCC, 2007).

2.1 CARBON SEQUESTRATION

IPCC (2007) defines carbon sequestration as an increase in carbon stock in any non-atmospheric reservoir. Carbon sequestration is the withdrawal of atmospheric carbon dioxide and its storage in terrestrial ecosystems for a long period.

Several studies consider terrestrial systems as viable carbon sinks as sufficient land area is available to mitigate significant shares of annual carbon dioxide emissions (Marland, 1988; Daniel and Tirpak, 1989; Trexier, 1991) and that this approach provides a relatively inexpensive means of addressing climate change (Sedjo and Solomon, 1989 ; Dudek and LeBlanc, 1990).

The 1997 Kyoto protocol recognizes that the withdrawing of CO_2 from atmosphere and sequestering it in to the biomass is the only practical way for mitigating the increased level of carbon dioxide release to atmosphere. Ravindranadh *et al.* (1997) reported that trees function as the vital sinks for atmospheric carbon dioxide by way of storing them in the standing biomass.

A stock that takes in carbon is called "sink" and one that releases out carbon is defined as a "source". Flows of carbon over time from one stock to another, for example, from the atmosphere to the forest land, are viewed as carbon "fluxes" (Waran and Patwardhan, 2001).

2.2 ABOVE GROUND CARBON SEQUESTRATION

Species, location, soil type and rainfall affect the sequestration potential of a tree (Dexter, 2000). During photosynthesis trees fix carbon hence they act as a sink for carbon dioxide and that fixed carbon get stored in biomass. The net long-term CO_2 source/sink dynamics of forests change through time as trees grow, die, and decay. Human influences on forests influences carbon dioxide source/sink dynamics of forests (Nowak and Crane, 2002).

For compensating this increased level of greenhouse gas (GHG) emissions, removal of atmospheric carbon (C) and storing it in the terrestrial biosphere is one of the proposed options. Silviculture lands act as a potential sink and could absorb large quantities of carbon. Agroforestry is given importance as a land-use system not only in terms of agricultural sustainability but also to solve the issues related to climate change (Alain and Serigne, 2003).

Living trees continue to absorb and store carbon whereas mature trees act as a reservoir of carbon (Guan *et al.*, 2016). India with 69.2 million hectare forest cover (FSI, 2013) including a wide range of forest types from wet to dry forest in temperate to tropical climate has high capacity in absorbing and retaining carbon (Guan *et al.*, 2016).

2.3 BELOW GROUND CARBON SEQUESTRATION

The first comprehensive study of Soil Organic Carbon (SOC) in Indian soils was conducted using data from different cultivated fields and forests with variable rainfall and temperature patterns (Jenny and Raychaudhuri, 1960). The study confirmed the effects of climate on C reserves in the soil. Soil organic carbon content is a balance between addition and decomposition rates and, as such, changes in ecosystems can bring about marked changes in both pool size and turnover rate of SOC and therefore nutrients. Small changes in total soil organic carbon are difficult to detect because of the high background levels and natural soil variability. For this reason, several attempts were made to use sub - pools as sensitive indicators of changes in soil organic carbon (Jenkinson and Rayner, 1977).

Grainger (1988) calculated that the tropics contain 758 million ha of depleted or degraded lands which were once forested. Reforestation of these areas would capture significant amounts of atmospheric carbon, and were expected to contribute to soil quality and conservation (Schroeder, 1992). Forestry activity designed to store carbon is often proposed for the tropics, as tropical climates support rapid vegetation growth (Schroeder and Ladd, 1991). Of the 130 M ha of forest plantations in the world (Allan and Lanly, 1991), just over half are located in the tropics (FAO, 1995).

Although there are several estimates of carbon storage in various forest types (Brown, 1993; Lugo and Brown, 1992; Vogt, 1991), few estimates of individual species carbon storage potential have been published. Using ecosystem areas from different sources and representative global average C densities, organic carbon (OC) in Indian soils was estimated as 23.4–27.1 Pg (Dadhwal and Nayak, 1993). Another attempt to estimate SOC stock was made by Gupta and Rao

(1994) who reported an SOC stock of 24.3 Pg for soil depths ranging from surface to an average depth of 44–186 cm in Indian soils. The study used a database that included 48 soil series. However, the first comprehensive report of SOC stock in India was carried out by Bhattacharyya *et al.* (2000) who estimated 9.5 Pg SOC at a depth of 0–0.3 m.

The forestry sector cannot only sustain its carbon but also has the potential to absorb carbon from the atmosphere. The rate of afforestation in India is one of the highest among the tropical countries, currently estimated to be 2 Mha per annum. The annual productivity has increased from 0.7 m3 per hectare in 1985 to 1.37 m^3 per hectare in 1995. Increase in annual productivity directly indicates an increase in forest biomass and hence higher carbon sequestration potential. The carbon pool for the Indian forests is estimated to be 2026.72 Mt for the year 1995. Despite the importance of tropical areas in terms of the percentage of global SOC stocks and the vulnerability of these stocks (Batjes, 1996), we still have relatively little information about soils in these regions and how they react to land use/land management practices.

The large changes in the quantity and turnover of soil organic carbon across landscapes and over long time spans may be due to variation in passive (mineral-stabilized) carbon in these aggregates (Torn *et al.*, 1997). The total carbon storage that can be credited to global forest plantations today is an estimated 11.8 Pg C (Winjum and Schroeder, 1997), and about 10 percent of it is lost every year through land conversion, since industrialization. Rates of land use change are greatest in the tropics where the demand for land is increasing with the increase in population. It is considered that the increasing concentration of greenhouse gases (e.g. CO_2, CH_4, N_2O, O_3) has led to changes in the earth's climate. Furthermore, there is agreement that human activities such as fossil fuel combustion, land-use change and agricultural practices have contributed substantially to the rise in atmospheric greenhouse gas concentrations (IPCC, 1997).

Marland (1998) estimated that based on higher potential growth rates, the area required to capture annual carbon emissions could be reduced by 25 percent if afforestation efforts were centered in the tropics. There is a growing need for computer simulation models that can assist in the estimation of carbon budgets (Mosier, 1998; Landsberg, 2003;Van Vliet *et al.*, 2003; Battaglia *et al.*, 2004).

Assuming that the present forest cover in India will sustain itself with a marginal annual increase by 0.5 Mha in area of plantations, we can expect our forests to continue to act as a net carbon sink in future (Lal and Singh, 2000).

Soil agreggates strongly influence the major physical and chemical properties of soil as well as soil organic matter and its chemical nature. Soil aggregates varies spatially as a function of plant as a function of soil development and disturbances and plays an important role in the stabilization of soil organic carbon (Laird, 2001).

To allow informed choices between species when establishing carbon storage projects, it is important to characterize various traits that influence carbon storage on a per species basis. Such information would also be useful for inclusion in global carbon storage/cycling models (Kraenzela *et al.,* 2003). Chhabra *et al.* (2003) estimated the organic C pool of Indian forest soils as 6.8 Pg C in top 1 m, using estimated SOC densities and Remote Sensing based area of forest types.

Forestry and afforestation in particular, regarded as an important activity that can offset the effects of greenhouse gas emissions. Projects that increase the area of plantations are suggested for inclusion under the Clean Development Mechanism (CDM) as defined in Article 12 of the Kyoto Protocol (Van Vliet *et al.,* 2003). However, significant uncertainties in the reliability of carbon pool and flux measurements make it difficult to determine the (net) carbon benefits of afforestation or forestry management practices. As a result, further investment in, and development of, the plantation industry is threatened (Van Vliet *et al.,* 2003).

Knorr *et al.*, (2005) concluded from their soil incubation studies that the decomposition of stable soil organic matter is even more sensitive to increases in temperature than that of labile pools, thereby exerting an even stronger positive feedback to global warming than assumed by current carbon cycle models. A significant positive correlation between the activation energy (Ea) and the log-transformed apparent turnover time of the sample was observed in many studies. The CO_2 evolution from soil is highly sensitive to temperature and global changes may have a great influence on the magnitude of CO_2 efflux. CO_2 efflux from soil to atmosphere is a major component of greenhouse gas emission and is a crucial pathway of the C cycle. Based on a five-decade record of chamber measurements, Bond-Lamberty and Thomson (2010) estimated that the global soil CO_2 efflux, widely referred to as soil respiration, was about 98 PgC per year in 2008., this is more than 13 times the rate of fossil fuel combustion (IPCC, 2007), indicating that 20–40 per cent of the atmospheric CO_2 circulates through soils annually.

2.4 CARBON DYNAMICS IN TEAK PLANTATIONS

Increasing concentration of greenhouse gases (e.g. CO_2, CH_4, N_2O, O_3) has led to changes in the earth's climate. Human activities such as fossil fuel combustion, land-use change and agricultural practices have also contributed substantially to the rise in atmospheric greenhouse gas concentrations (IPCC, 1997). The Studies of Kraenzel *et al.*, (2003) concludes that teak plantations have appreciable mean carbon storage capacity, much greater than that of the abandoned pasture where they were planted. The compartment of the plantation with the greatest potential for carbon sequestration and carbon storage is the wood biomass (120 t C ha-1). Forestry and afforestation in particular, is regarded as an important activity that can offset the effects of greenhouse gas emissions. Projects that increase the area of plantations were suggested for inclusion under the Clean Development Mechanism (CDM) as defined in Article 12 of the Kyoto Protocol (Van *et al.*, 2003). However, significant uncertainties in the reliability of carbon pool and flux measurements make it difficult to determine the (net) carbon benefits of afforestation or forestry management practices. As a result, further investment in, and development of, the plantation industry is threatened (Van Vliet *et al.*, 2003). There is a growing need for a comprehensive knowledge on carbon stocks, pools and their thermal sensitivities with teak rotations in the Kerala Western Ghats (Mosier, 1998; Landsberg, 2003;Van *et al.*, 2003; Battaglia *et al.*, 2004).

Thomas (2005) establishes that management activities undertaken and site qualities have a strong impact on the performance of the *T. grandis* plantations, hence its soils and biomass carbon storage potentials. The ability of teak in sequestrating carbon is controlled by age class or growth level. Khanduri, *et al.*, (2008) presented that in the oldest teak which is represented by larger trunk diameter, the stored carbon is also higher, around 699.01m^3 ha^{-1}, while according to Grant (2008) a 21-year-old teak will store 1,037 kg of carbon.

Studies of Derwisch *et al.*, (2009) in *Tectona grandis* plantations of Western Panama says that average aboveground C storage ranged from 2.9 Mg C ha^{-1} in the 1-year-old plantations to 40.7 Mg C ha^{-1} in the 10- year-old plantations. They estimated the potential aboveground C storage of the teak plantation over a 20 year rotation period, using regression analysis. The CO2-storage over this period amounted to 191.1 Mg CO2 ha-1.

Sreejesh *et al.*, (2013) worked out the carbon storage in different compartments of teak (*Tectona grandis*) in each of the following felling periods: 5, 10, 20, 30, 40 and 50 years of age to arrive at an estimate of its carbon sequestration potential. It was found that around 181 t C/ ha is stored by teak plantations in Kerala during its life time of 50 years. Thomas *et al.*, (2013) reported that mature plantations of teak act as reservoir while young plantations sequester large amount of carbon. Further, teak has a long carbon locking period compared to short duration species and has added advantage that most of the teak wood is used in indoors thereby extending the locking period.

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Carbon pool is heavily affected by biomass. Therefore, factors affecting biomass potency will also affect carbon intake. For example, thinning results in decreased competition among trees, allowing higher quality of tree growth and plantation dimension. Tree age will increase the amount of carbon intake because the older the tree, the bigger the dimension and higher the potential of carbon storage (Mochamad and Aniek, 2014).

Information about patterns of changes in carbon storage, in particular on teak forests is vital and urgent so that it could be used to help as a determinant of forest management and environmental policies. It helps to predict and identify deposit patterns or carbon storage and changes as early as possible, and to determine the next steps based on the information and the demands of Clean Development Mechanism (CDM) (Mochamad and Aniek, 2014).

The biomass and carbon content of teak plantations increase in every increased plant age and the quality of growing site of plantations. This is due to the increased plant age resulting from bigger plants as well as better growing areas which provide a better nutrient element. (Mochamad and Aniek, 2014).

CHAPTER 3

MATERIALS AND METHODS

3.1 STUDY AREA

Teak (*Tectona grandis* Linn. f), the queen of timber is the most important forest plantation species of Kerala in every respect. The study was carried out in Nilambur Taluk, Kerala where the first teak plantation in India was raised in the year 1842 by the British.

Nilambur in Malappuram district of Kerala lies between $11^0$26'70" and $11^0$36'61" N latitudes $76^0$22'58" and $76^0$45'10" E longitudes. Nilambur forest area spans a large land area and hence is divided into Nilambur North Forest Division with an area of 39 592.491 ha and Nilambur South Forest Division with 36 515.27 ha. Nilambur, Edavanna and Vazhikadavu ranges constitute the Nilambur North Division while Karulai and Kallikavu ranges constitute the South Division. The study sites were located in Nedumkayam and Padukka forest station under Karulai range in South Division with teak plantations of different ages and rotations.

3.2 CLIMATE

The climate is humid tropical with both South-West and North-East monsoons. Summer rains are also not uncommon. On an average, the area receives around 2500 mm rainfall, 60-70 percent of which is contributed by the South-West monsoon, 20-30 percent by North-East monsoon and rest received during the summer months. Temperature fluctuates between 21 to 38°C and the humidity varies from 60 to 90 per cent.

3.3 GEOLOGY AND SOIL

The geology of the region is constituted by crystalline rocks of archean ages, the most common being gneiss which is mostly granitic and is easily recognizable by the alternate bands of pale and dark bands, the pale bands being dominated by quartz and feldspar and the darker shades by predominantly biotite. The soil formed from the gneissic parent material is coarse textured, acidic and with low exchange capacities because during the weathering process under the influence of hot humid tropical climate most of the silica and the bases had been leached down resulting in iron-aluminum-manganese rich surface horizons of soil. These soils are often referred to as lateritic/ ferrallitic soils indicating its genesis through the process called laterisation. The soil strata have well developed profiles due to intensive leaching. Appreciable amount of gravel is found in the soil mass providing good internal drainage. Accumulation of humus in the top soil gives it dark reddish brown to dark brown colour, which changes to different shades of red in the sub soil due to de-hydration of sesquioxides. The surface soil has a granular structure, which favours aeration, infiltration and root development.

3.4 SOIL SAMPLE COLLECTION

Soil samples were collected in a chronosequence from 16 plantations. These plantations were grouped into four age groups of continuous teak growth (30-50, 50-80, 80-110 and >110 years). Plantations where selected in each group based on their probability proportional to size and a minimum of three replications were maintained in each of these age group. Teak has a mean rotation age of 50 years in Kerala. Age group 30 -50 indicates 30 – 50 years of teak cultivation, 50 – 80 indicates that a second rotation is in progress after clear felling first rotation and the soils are continuously under teak for the past 50 -80 years and age group 80 – 110 indicates that a third rotation is in progress. Age group >110 is the group where teak was raised nearly 110 years back and has not felled till now.

Surface soil samples (0 – 20 cm) were taken in a toposequence in each of the selected sites and used for the study. Enough number of such pits were taken depending on site factors. Geographical coordinates were marked for all sampling points. Samples were packed in air tight containers and taken to the laboratory. Collected samples were separated into two, one part was air dried and sieved through 2mm sieve and other part was sieved using a wet sieve (sieves were 0.2mm, 0.6mm, 1mm, 2mm, 4mm) and >250μm aggregates were mixed to obtain macro aggregates and <250µm to obtain micro aggregates. From each of the selected plantation, soils were also collected upto 1 m depth for carbon stocks estimation.

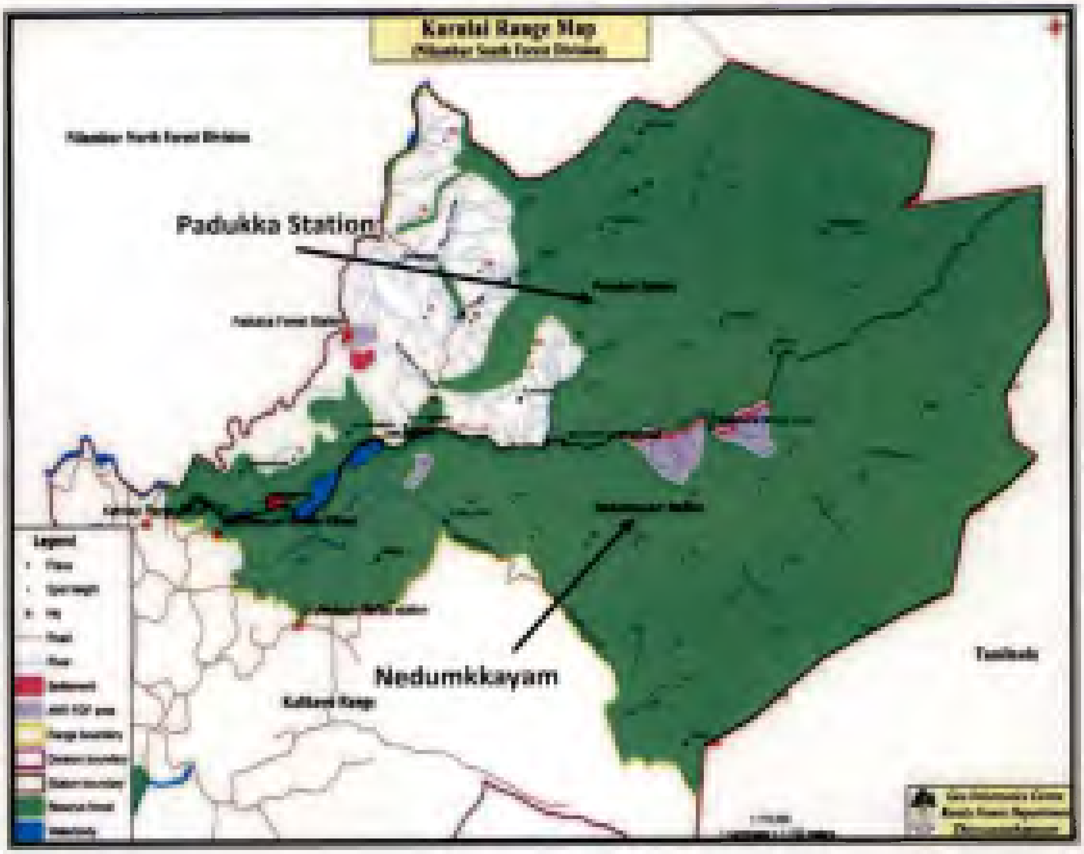

Figure.1 Schematic map of the study area (Source: Kerala Forest Department)

Table.1 Sample site description

Site	Forest Range	Geocoordinates
TP NEDUMKAYAM 1980	Nedumkayam	N 11° 16′ 59.7′′ E 076° 20′ 11.4′′
TP NEDUMKAYAM 1971	Nedumkayam	N 11 °17′ 11.8′′ E 076 ° 19′11.6′′ 53m
TP SHANKARANKODE 1965	Padukka	N 11 ° 18′21.1′′ E 076 ° 19′ 47.0′′ 56m
TP SANKARANKODE 1961	Padukka	N 11° 18′ 24.1′′ E 076°19′45.3′′ 48m
TP POOLAKKAPARA 1989	Padukka	N 11°20′ 08.9′′ E 076 °22′ 57.7′′ 62m
TP NEDUMKAYAM 1985	Nedumkayam	N 11 ° 17′ 18.6′′ E 076 ° 19′ 45.5′′ 50m
TP MUNDAKADAVU 1982	Padukka	N 11° 18′26.6′′ E 076 °21′43.7′′ 74m
TP NEDUMKAYAM 1974	Nedumkayam	N 11 °16′ 44.4′′ E 076 ° 19′ 35.0′′ 42m
TP POOLAKKAPARA 1969	Padukka	N 11 °21 ′19.6′′ E 076° 22′ 0.31′′ 47m
TP EZHUTHUKAL 1963	Nedumkayam	N 11 °16′ 52.5′′ E 076 ° 22′ 01.4′′ 79m
TP NEDUMKAYAM 1909	Nedumkayam	N 11 ° 17′ 18.6′′ E 076 ° 19′ 59.0′′ 47m
TP KANJIRAKADAVU 2006	Nedumkayam	N 11° 18′ 18.7′′ E 076 °23′ 20.8′′ 98m
TP POOLAKKAPARA 2001	Padukka	N 11 °21 ′19.6′′ E 076° 22′ 0.31′′ 47m
TP KANJIRAKADAVU 1996	Nedumkayam	N 11° 18′ 15.3′′ E 076° 22′ 18.1′′ 84m
TP KANJIRAKADAVU 1990	Nedumkayam	N 11° 18′ 20.1′′ E 076° 22′ 34.5′′ 102m
TP KALLENTHODE 1966	Padukka	N 11° 17′ 41.8′′ E 076° 18′ 23.1′′ 40m

3.5 PLANT SAMPLE COLLECTION

Plant samples were collected for assessing biomass stored carbon in herbs, shrubs and trees in these plantation. For collecting the understory vegetation from plantations, ten quadrats of 3 m×3 m and 1 m×1 m were laid for shrubs and herbs, respectively. Complete harvesting of all shrub and herb species present in these quadrats were done.

Litter samples were collected from plantations by laying ten 5 m × 5 m plots at the time of peak litter fall. Both litter and understory samples were oven dried and powdered before chemical analysis.

Diameter at breast height (GBH) of ten random trees from each plantations were measured for tree carbon estimation using allometric equations.

3.6 ANALYSIS OF BASIC SOIL PARAMETERS

3.6.1 pH

The pH of soil was determined in 1:2.5 soil water suspension. 10 g sample of soil was shifted through 2 mm sieve in a 50 ml beaker. 25 ml of distilled water was added, stirred well for about 5 minutes and kept for half an hour. Stirred well again and took the reading using pH meter (Jackson, 1958).

3.6.2 Electrical conductivity

The clear supernatant of 1:2.5 soil water suspension prepared for pH measurement was used for estimation of electrical conductivity. Conductivity meter was calibrated using 0.01N KCl solution (Jackson, 1958).

Plate 1. Sample collection and preparation

3.6.3 Mean weight diameter (MWD)

The stability of the soil aggregates expressed as mean weight diameter (MWD) was deduced by wet sieving of soils. Five size classes were used as: < 0.2, 0.2 - 0.6, 0.6 -1.0, 1.0 - 2.0 and 2.0- 4.0 mm. The mean weight diameter (MWD) of the soil aggregates was calculated according to the formula (Van Barel, 1950).

MWD= $\sum_{j=1}^{k} W_j \bar{X}_j$..........Eq.(1)

where,

MWD = mean-weight diameter, (mm)

$\bar{X}_j$= arithmetic mean diameter of the j-1 and j sieve openings (mm)

Wj = proportion of the total sample weight (uncorrected for sand and gravel) occurring in the fraction (dimensionless)

k = total number of size fractions (in this case 5)

3.6.4 Soil texture and bulk density

The texture analysis of experimental soils was carried out using the international pipette method and bulk density estimated by core method.

3.6.5 Nutrient content

Available nitrogen was estimated by alkaline permanganometry (Subbaiah and Asija, 1956), available phosphorous by Bray No. 1 extraction and spectrophotometry, neutral normal ammonium acetate extractable potassium by flamephotometry, neutral normal ammonium acetate extractable calcium and magnesium by atomic absorption spectrophotometry (Jackson, 1958). Available Fe, Mn, Zn and Cu was extracted using 0.1 N HCl and estimated in an atomic absorption spectrophotometer and hot water extractable boron was assessed colorimetrically by azomethine H method.

3.6.6 Cation exchange capacity

Cation exchange capacity of the soils were estimated by $BaCl_2$ method.

3.6.7 Soil organic carbon partitioning

Soil carbon partitioning was examined with respect to different carbon fractions in the processed soil. The detailed methodology is as follows.

3.6.8. Total organic carbon (TOC)

Total organic carbon in soil was determined by CHNS analyzer (EURO EA3000). 5 - 10 mg of well pulverized samples were used for the estimation. The instrument settings used were as follows:

Carrier flow (ml/min) : 120 ± 5

Carrier (kPa) : 80

Purge (ml/min) : 80

Oxygen (ml) for 5 x 9 mm tin caps : 20

ΔPO_2 (kPa) : 35

Oxidation time (sec) : ≈8

Sampling delay (sec) : ≈6

Run time (sec) : 320

Front furnace temperature (°C) : 980

GC oven temperature (°C) : 115

Detector : TCD

3.6.9 Walkley and Black organic carbon (WBC)

Walkley and Black Organic Carbon represents easily oxidisable fraction of total organic carbon. This fraction was determined in soil samples passed through 0.2 mm sieve by wet digestion method of Walkley and Black (1934).

3.6.10 Active carbon

Active or labile carbon represents the bio – available form of organic carbon that has a low turnover time (< 5 yrs). Active carbon was determined using the $KMnO_4$ oxidation method, in which soil samples containing about 15 mg organic carbon were put into 333 mMol L^{-1} $KMnO_4$ solution (25 ml) and oscillated for 1 hour to oxidize active carbon. The amount of active organic carbon was quantified by the amount of $KMnO_4$ consumption determined spectrophotometrically (Blair et al.,2005).

3.6.11 Passive carbon

Passive organic carbon represents the recalcitrant form of organic with mean residence time of 200 -1500 years. This fraction was measured by using acid hydrolysis (Leavitt et al., 1996), taking more than 5 g of soils into a test tube containing 6 N HCl and boiling them for 16 hours. The samples were washed to pH=7.0 with distilled water, dried in an oven of 60 °C and the carbon of these samples quantified as passive carbon by CHNS analyzer (EURO EA3000).

3.6.12 Slow carbon

Slow carbon is considered as an intermediate between active and passive carbon fractions with a mean residence time of about 20 - 40 years. Slow carbon was taken as the difference between the TOC and the sum of active and passive carbon.

3.6.13 Soil carbon stocks

Soil carbon stocks were estimated up to 1m depth to have a better understanding of the changes in terrestrial reservoir of soil organic carbon in the teak plantations with continuous rotation. Soil pits were taken in a toposequence to a depth of 100 cm in each of the selected sites and samples were separated into depths of 0–20, 20–40, 40–60, 60–80 and 80–100 cm. Core samples were also taken from these depth intervals for bulk density estimations. Total carbon in the soil collected from different depths were estimated (CHNS EURO EA 3000) and used for carbon stocks calculations using the following formula by Batjes (1996):

$$\mathrm{Cm} = \sum_{i=1}^{n} \mathrm{BD} * \mathrm{TC} * \mathrm{d} * (1 - \mathrm{Si}) \ldots\ldots \mathrm{Eq.}(2)$$

Where,

C_m = Carbon stocks (Mg m^{-2})

Tc_i = Total carbon of i^{th} layer (g C/ g)

B_i = Bulk density of i^{th} layer (kg C ha^{-1})

d_i = Depth of i^{th} layer (m) .

3.6.14 Thermal stability studies

Soil samples collected from the surface 0 – 20 cm depth of different teak plantations were sieved by wet sieving , air-dried and used for the thermal stability of SOC. Samples were separated in to macro (>2mm) and micro (<2mm) aggregates by wet sieving. The decomposition rate and activation energies of soil carbon were investigated by an incubation experiment of 45 days duration. Soil samples (8g) were incubated in wide mouth bottles after estimating the initial organic carbon, passive carbon and labile carbon. Four incubation temperatures that is., 25°C, 30°C, 35°C and 40°C were used for the study. The carbon fractions in the incubated soil were estimated at regular intervals (0, 3, 6, 9, 12, 15, 18, 30 and 45 days). The carbon lost during the period was estimated by subtracting the amount lost during the period from the initial carbon content (at 0^{th} day) and was used for determining the first order rate kinetics using the equation:

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$A_t = A_0e^{-kt}$ ....Eq. (3)

where,

k is the decomposition rate constant

A0 and At are the amount of organic carbon at zero

't' time.

The activation energy (Ea) was calculated using Arrhenius equation:

$k = A \exp(-Ea/RT)$ ....Eq. (4)

where,

k is the decomposition rate constant

A is the frequency factor

Ea is the required activation energy in joules per mole

$R = 8.314\ J\ K^{-1}\ mol^{-1}$

T is the temperature (K)

Ea was calculated from the slope (Ea/R) obtained by plotting ln k against 1/T (Knorr et al. 2005).

Q_{10} indicates the responses of biological processes with temperature. Q_{10} values were calculated as a function:

$Q_{10} = (k2/k1)^{(10/T2 - T1)}$ ....Eq. (5)

where

k2 and k1 are the reaction rates at temperatures

T_2 and T_1 respectively (T_1=298 K and T_2=308 K) (Kirschbaum 1995).

3.6.15 CO_2 Efflux studies

Soil samples collected from the mineral horizon (A - horizon) of different teak plantations were sieved in 2mm sieve and used for the CO_2 efflux studies. Thirty days incubation study was conducted at four different temperatures (25°C, 30°C, 35°C and 40°C). Fifty gm of soil maintained at field capacity were taken in wide mouth bottles which can be closed tightly using a lid. Inside this bottles vials having 5ml of 0.5N NaOH were introduced using a twine. CO_2 trapped in this NaOH were analyzed at regular intervals (3, 6, 9, 12 , 15, 18, 21, 24, 27, 30) by titrating it against 0.25N HCl.

3.6.16 Statistical analysis

Analysis of variance (ANOVA) was performed using IBM SPSS version 20.0.Treatment means were compared at $P < 0.05$ level using the least significant difference (LSD) for all the parameters.

Plate 2. Soil aggregates in incubator for thermal stability studies

Plate 3. Assembly for determination of CO_2 evolution from soil by alkali trap method

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CHAPTER 4

RESULTS

Variation of basic soil parameters with period of continuous teak rotation is presented in Table 2. The soils were found to vary from sandy loam to loamy sand and acidic in reaction (pH). The analysis of variance showed that the soil pH does not have significant variation with rotation of teak (age group). The maximum soil pH was observed in the 50 - 80 age group (5.80), followed by the age group 30 -50 (5.66). The plantations which had been retained without felling and had an age of >110 years was found to have the lowest pH values (5.38). Electrical conductivity was also found not to vary significantly between the groups and the values ranged from 32.47 µS m^{-1} to 47.65 µS m^{-1}. The base saturation and cation exchange capacity of the soils varied from 27.2 - 31.2 per cent and 5.8 - 11.8 cmols(p+)kg^{-1}.

Mean weight diameter, a measure of the soil aggregate stability, was found to be highest (1.41) in plantations which were retained without felling (age group 4). The MWD values were found to decrease in the second (age group 2) and third rotations (age group 3) by 39 per cent and 50 per cent respectively.

Soil nutrients observed in plantations with period of continuous teak rotation is given in Table 3. Among the primary nutrients, nitrogen was found to reduce drastically by the third rotation (34.28 mg kg^{-1}). On the other hand available phosphorus content in the plantation without felling shows almost half the value of plantations that have rotations. No significant variation was found in available potassium content among the age groups. No definite pattern was observed for the available micronutrient content in the different age groups.

Table 2.Variations in basic soil parameters with period of continuous teak rotation

Age group (years)	Texture	pH	EC (µS m^{-1})	Bulk density (Mg m^{-3})	Mean weight diameter (mm)	Base saturation (%)	CEC (c mols (p+) /kg)
30-50	Loamy sand	5.66	46.88	1.40	1.30	29.5	9.6
50-80	Sandy loam	5.80	47.65	1.48	0.70	27.7	5.8
80-110	Sandy loam	5.58	36.49	1.39	0.86	27.2	6.4
>110	Sandy loam	5.38	32.47	1.32	1.41	31.4	11.8
NS - non significant							

Table 3. Soil nutrients observed in plantations with period of continuous teak rotation

Age group (years)	N	P	K	Ca	Mg	Fe	Mn	Cu	Zn	B
	Kg ha^{-1}			mg kg^{-1}						
30-50	88.03	14.96	30.87	60.44	14.49	14.34	62.95	2.66	2.43	0.27
50-80	96.72	18.21	31.36	80.46	25.51	16.80	48.16	2.35	2.90	0.27
80-110	76.79	16.82	32.10	85.23	22.26	17.01	42.06	2.41	1.87	0.31
>110	79.3632	7.9744	31.07	46.98	22.18	9.79	26.95	3.48	1.76	0.51
NS - non significant										

4.1 SOIL CARBON STOCK

Variation of carbon stock in teak plantations with different periods of continuous growth is shown in table 4. The soil carbon stocks varied from 4.21 – 5.85 kg.m^{-2} in the teak plantations of different rotation age. There was no significant variation among age groups with respect to the carbon stocks indicating that disturbance by way of clear felling and silvicultural operations did not significantly affect the carbon stocks in teak plantations of Western Ghats. In general, the surface layers (0 – 20 cm) had the highest concentration of carbon content (1.64 per cent– 2.17 per cent) and the values decreased with depth (Table 5).

The carbon distribution with depth within the soil profiles in different age groups is given in table 5. It was found that 70 – 75 per cent of the total carbon stocks in the different age groups of Kerala Western Ghats are distributed in the 0 - 60 cm depth. The upper 0 - 20 cm layer contains 35 – 40 per cent of the total carbon stocks. The surface and subsurface layers with active root concentration i.e., 0 - 60 cm stores approximately 70-75 per cent of the total stocks in these teak plantations. Beyond 60 cm carbon is added mainly by way of translocation from the surface and was found to have 10 -15 per cent of the total stocks. Most of the studies assessing carbon stocks of forest systems considers only the 0 - 30 cm depth for soil carbon stock assessment and this study establishes that calculation of soil carbon stocks up to this depth alone will grossly underrepresent the actual carbon storage potential of our tropical forest systems.

Similar to total organic carbon content, organic carbon in microaggregates also showed a decreasing trend with depth in all age group (Table 6). In the surface horizon (0 – 20 cm) the highest organic carbon content was found in second rotation plantation (age group 50 -80) whereas plantations without felling had the maximum content at 80-100cm. It was found that with continuous teak growth, increasingly higher amounts of carbon was translocated to the lower layers and variation in carbon between the layers was at a minimum.

Table 4. Variation of carbon stock in teak plantations with different periods of continuous growth

Age group (years)	Carbon stock (kg C m^{-2})
30-50	5.85
50-80	4.46
80-110	5.72
>110	4.21
NS - non significant	

Table 5. Variation in organic carbon content (%) with soil depth in teak plantations with different periods of continuous growth

Depth (cm)	Age group (years)			
	30-50	50-80	80-110	>110
	Organic carbon (%)			
0-20	2.05	2.17	2.05	1.64
20-40	1.30	0.37	1.00	1.21
40-60	0.61	1.05	0.60	0.80
60-80	0.76	0.19	0.76	0.58
80-100	0.25	0.68	0.36	0.57
NS - non significant				

Table 6. Variation in soil microaggregate organic carbon content (%) with soil depth in teak plantations with different periods of continuous growth

Depth (cm)	Age group (years)			
	30-50	50-80	80-110	>110
	Organic carbon (%)			
0-20	0.55	0.82	0.81	0.76
20-40	0.44	0.47	0.52	0.55
40-60	0.31	0.32	0.35	0.33
60-80	0.16	0.29	0.17	0.27
80-100	0.10	0.17	0.12	0.21
NS - non significant				

Table 7. Variation in soil microaggregate organic carbon content (%) with soil depth in teak plantations with different periods of continuous growth

Depth (cm)	Age group (years)			
	30-50	50-80	80-110	>110
	Organic carbon (%)			
0-20	0.92	0.96	1.14	1.22
20-40	0.77	0.73	0.98	0.86
40-60	0.60	0.37	0.64	0.65
60-80	0.50	0.31	0.45	0.46
80-100	0.34	0.22	0.24	0.42
NS - non significant				

Variation in soil microaggregate organic carbon content (%) with soil depth in teak plantations with different periods of continuous growth is presented in table 7. Macroaggregates in soils of different age groups were found to store nearly two times higher amount of organic carbon than microaggregates. Highest organic carbon content in macroaggregates was found in the surface layers (0 – 20 cm) of plantations without felling (1.22 %). Continuous teak rotation was found to gradually increase the organic carbon content in the macroaggregates of surface layers from 0.92 percent in age group 30 – 50 to 1.22 per cent in plantations without felling (age group >110) .

Age groups of trees were found to influence the turnover of carbon in soil. Active and slow fractions with comparatively lesser turnover times (0 -5 years and 20 – 40 years, respectively) are essential for the ecosystem sustainability compared to the passive recalcitrant forms with turnover times of 200 to thousands of years. In age group 30 - 50, the soils were found to contain 0.11 per cent, 0.60 per cent and 0.39 per cent of active, slow and passive carbon respectively (Table 8). In all the age groups, the combination of active and slow carbon pools were found to be nearly double to that of the passive fraction (Table 8). Total carbon was found to show an increasing trend from first (1.11%) to third (1.56%) rotation plantation (age group 30 – 50 to age group 80 -110).

In microaggregates of the age group 30 - 50, passive carbon was found to be the dominant fraction accounting for nearly 50 per cent of the total organic carbon in soil (Table 9). Though continuous teak growth (age groups 50 -80, 80 - 110 and >110) was found to increase the total carbon content of microagreggates, it was found to be stored more as slow carbon pools with the values ranging from 0.51 – 0.53 percent and a corresponding decrease was observed for the passive fractions. This indicates that a dynamic equilibrium exists between the slow and passive fractions in these aggregates. Irrespective of period of teak planting, the active carbon was found to be on par at all the sites.

Table 8. Variation in active, slow and passive carbon fractions (%) in teak plantations with different periods of continuous growth

Age group (years)	Active carbon (%)	Slow carbon (%)	Passive carbon (%)	Total carbon (%)
30-50	0.11	0.60	0.39	1.11
50-80	0.16	0.61	0.55	1.33
80-110	0.12	1.04	0.39	1.56
>110	0.11	0.72	0.56	1.40
NS - non significant				

Table 9. Variation in active, slow and passive carbon fractions (%) of microagreggates in teak plantations with different periods of continuous growth

Age group (years)	Active carbon (%)	Slow carbon (%)	Passive carbon (%)	Total carbon (%)
30-50	0.12	0.15	0.28	0.55
50-80	0.10	0.53	0.18	0.82
80-110	0.13	0.51	0.15	0.81
>110	0.12	0.51	0.12	0.76
NS - non significant				

Variation in active, slow and passive carbon fractions (%) of macroaggregates in teak plantations with different periods of continuous growth is presented in table 10. Active carbon fractions in the macroagreggates of different age groups were found vary from 0.11 -0.18 per cent. Slow carbon in macroagreggates was found to be highly influenced by period of continuous and the values ranged from 0.44 – 0.89 percent. The slow carbon concentration in

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macroaggregates of age groups 80 -110 (0.89%) and >110 (0.74%) was about 2 times higher than that of the content in age group 30 - 50 (0.44%) and 50 -80 (0.45%). Passive carbon concentration showed no variation among the macroaggregates with different age groups.

A major part of terrestrial carbon stock is also stored by tree biomass. Carbon stored in understorey vegetation was found higher in 30-50 age group plantation (3.92 kg C ha^{-1}). As the period of rotation proceeds , a decrease in understory carbon and the plantation without rotation was observed (2.19 kg C ha^{1}). Analysis of variance for carbon in understory vegetation shows that they are statistically insignificant. However, carbon analysis in litter across age group shows that 30-50 age group was significantly different from 50-80 and 80-110. 50-80 age group plantation was found to be statistically on par with 80-110 and >110.

Table 10. Variation in active, slow and passive carbon fractions (%) of macroaggregates in teak plantations with different periods of continuous growth

Age group (years)	Active carbon (%)	Slow carbon (%)	Passive carbon (%)	Total carbon (%)
30-50	0.12	0.44	0.35	0.92
50-80	0.18	0.45	0.32	0.96
80-110	0.11	0.89	0.14	1.14
>110	0.12	0.74	0.35	1.22

NS - non significant

Table 11. Variation in above ground carbon stocks of teak plantations with different periods of continuous growth

Age group (years)	Carbon in understorey vegetation (kg c ha^{-1})	Carbon in litter (kg c ha^{-1})	Carbon in tree biomass (kg c ha^{-1})	Total terrestrial carbon stock (kg c ha^{-1})
30-50	3.92	9.60^{a}	186.68	200.2
50-80	2.99	6.35^{bc}	294.78	304.12
80-110	2.76	4.37^{c}	266.38	273.51
>110	2.19	8.10^{ab}	318.64	328.93
Values with similar superscript do not differ significantly				

Variation in above gound carbon stocks of teak plantations with different periods of continuous growth is shown in Table 12. Analysis of variance for comparing reaction rate of carbon stored in micro aggregates at different age groups were found to be statistically significant. Reaction rate of microaggregates in 30-50 age group and >110 age group were same and significantly different from that of 50-80 and 80-110 age groups at 25°C. At 40°C, 30-50 and >110 age groups microaggregates had a carbon decomposition rate of 0.03 mmols C day^{-1} and were significantly higher than the 80 -110 age group indicating that though more carbon is stored in this fraction with period of rotation it may not be resistant to decomposition. Moreover, the reaction rates of carbon stored in the microaggregates of age groups 30 -50 and >110 were found not to vary with rises in temperature.

Reaction rates of carbon stored in the macroaggregates of age groups 50 – 80 and 80 -110 had a comparatively higher reaction rate than microaggregates at 25 °C. However, the reaction rates were found to increase by 100 percent when the temperature was raised from 25 °C to 40 °C. In macro aggregates at 25°C, highest reaction rate of 0.05 mmol C day^{-1} was observed in age group >110 plantation which remained unaltered when the temperature was raised to 40°C.

The activation energy for decomposition of organic carbon in microaggregates ranged from 29.57 to 52.98 kJ mol^{-1} and in macroaggregates from 23.92 to 51.25 kJ mol^{-1} (Table 13). In general, age group >110 plantations had significantly higher activation energies for carbon stored in micro- and macro - aggregates than all other plantations indicating a higher stability against decomposition in less disturbed soils. Carbon stored in the macro aggregates of 30-50 age group plantation shows most vulnerability to decomposition as indicated by their activation energy (23.92 kJ mol^{-1}) which was in par with that of 50-80 age group and significantly lower than other age groups.

Table 12. First order rate constants (k) of carbon decomposition at different temperatures in soil macro and micro aggregates of teak plantations with different periods of continuous growth

Age group (years)	Microaggregates		Macroaggregates	
	Rate constant (k) in mmols C day^{-1} at 25°C	Rate constant (k) in mmols C day^{-1} at 40°C	Rate constant (k) in mmols C day^{-1} at 25°C	Rate constant (k) in mmols C day^{-1} at 40°C
30-50	0.03^{b}	0.03^{b}	0.04	0.05
50-80	0.07^{a}	0.08^{a}	0.04	0.08
80-110	0.07^{a}	0.08^{a}	0.03	0.06
>110	0.03^{b}	0.03^{b}	0.05	0.05
Values with similar superscript do not differ significantly				

Table 13. Activation energy ($kJmol^{-1}$) of carbon decomposition in soil macro and micro aggregates of teak plantations with different periods of continuous growth

Age group (years)	Activation energy (kJ mol^{-1})	
	Micro aggregates	Macro aggregates
30-50	29.57^{b}	23.92^{c}
50-80	52.98^{a}	28.62^{c}
80-110	34.72^{b}	38.74^{b}
>110	48.23^{a}	51.25^{a}
Values with similar superscript do not differ significantly		

Table 14. Q_{10} values of carbon decomposition in soil macro and micro aggregates of teak plantations with different periods of continuous growth

Age group (years)	Q_{10}	
	Micro aggregates	Macro aggregates
30-50	1.21	1.4
50-80	0.68	1.37
80-110	0.55	0.89
>110	1.4	1.4
NS - non significant		

The result of Q_{10} showed that there is a decrease in Q_{10} values with the plantation age. Plantation without felling indicated similar Q_{10} values for both macro and microaggregate and was higher than all other age groups (1.4). Third rotation plantation (age group 80 -110) showed the minimum value for both micro - (0.55) and macroaggregates (0.89). Carbon stored in the macro aggregates were found to respond more readily to decomposition than microaggregate carbon as indicated by their higher Q_{10} values.

4.2 CARBON DIOXIDE EFFLUX FROM SOIL

The cumulative carbon dioxide evolution was found to be the lowest in the third rotation plantation than all other age groups at both the studied temperatures of 25°C and 40°C. The cumulative CO_2 efflux under different age grouped teak plantations varied from 6.32 – 37.81mg C/ 100 g soil at 25°C and 8.39 - 58.56 mg C/ 100 g soil at 40°C. At 25°C, age group 30 -50 (first rotation) and age group >110 (plantation without felling) were found to have comparable cumulative CO_2 effluxes which corresponds to their active carbon contents. The CO_2 evolution in all age groups was found to be more at 40°C than at 25°C. There was a loss of 23.64 mg C/ 100g soil during the 30 days of incubation when the temperature was raised from 25°C to 40°C day in 30-50 age group plantations. More carbon was lost from second (age group 50 -80) and third rotation plantations (age group 80 -

110) compared to age group 30 -50 and plantations without felling (age group >110). However, the difference between the carbon lost at the studied temperatures were less in second and third rotations than age group 30 -50 and plantations without felling. This indicates that healthy systems with high labile carbon fractions will be maximum vulnerable to carbon losses under predicted climate change scenarios.

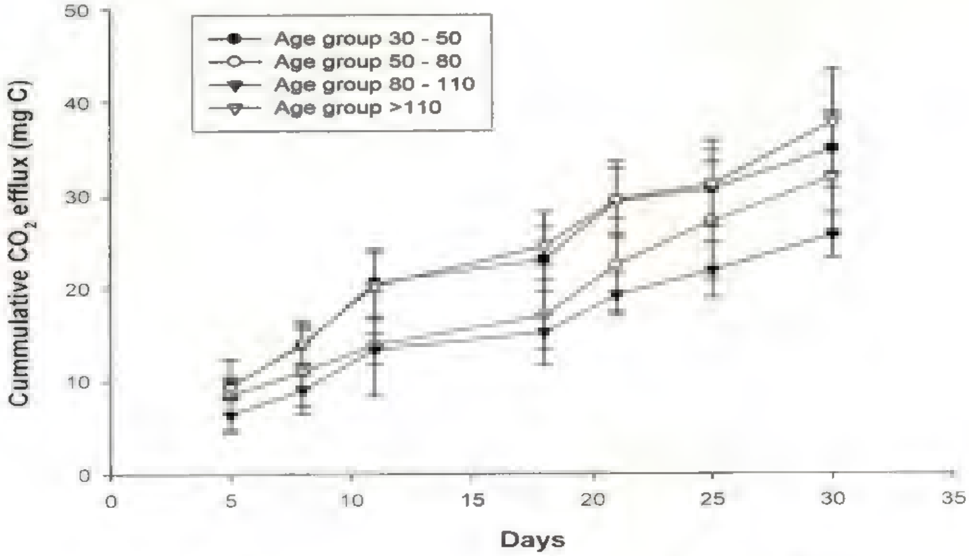

Fig 2. Cumulative carbon dioxide efflux at 25^0C

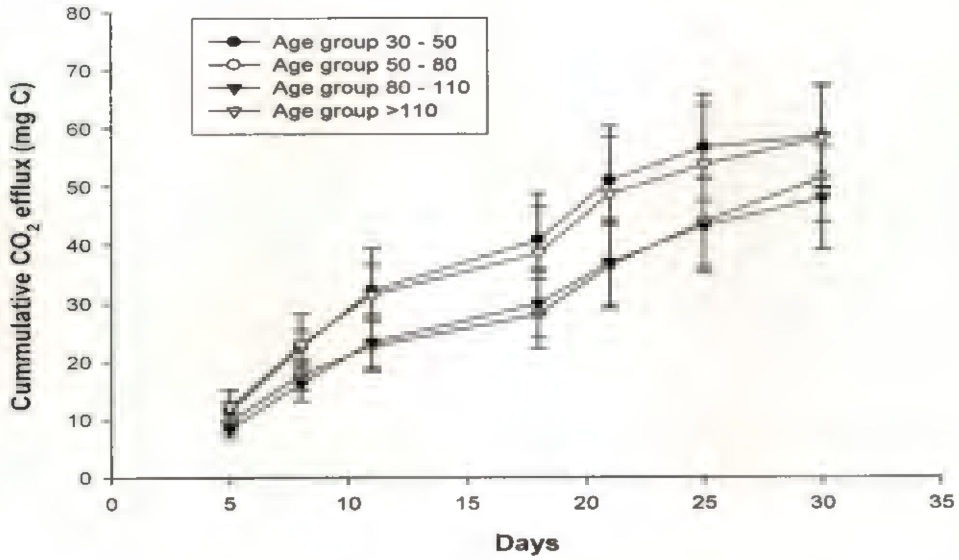

Fig 3. Cumulative carbon dioxide efflux at 40^{0}C

CHAPTER 5

DISCUSSION

Forests are the natural storehouse of biomass and carbon. They sequester and store more Carbon than any other terrestrial ecosystem and are important natural 'brakes' on climate change (Gibbs *et al.,* 2007). Forest management practices can be used to reduce the accumulation of greenhouse gases in the atmosphere through two different approaches. One approach is to actively increase the amount or rate of accumulation of carbon in the area. The second is to prevent or reducing the rate of release of carbon already fixed. Plantations are a very efficient way of promoting biomass and carbon accumulation, and tend to be easier to manage than multi-species stands or natural forests (Evans, 1992). Potential of forest tree plantations to absorb and store carbon is recognized to play a major role in the future mitigation of climate change (Canadell *et al.,* 2007). Therefore, the present study was carried out to quantify the carbon stock and to analyze thermal stability of aggregates and carbon dioxide efflux from these soils under an age series of teak plantation.

Most predominant soil texture in the teak plantations was found to be the sandy loam. The increase of pH at the starting of second rotation was attributed to biomass burning and subsequent base addition before second rotation. Mean weight diameter was used as a measure of aggregate stability. Fig. 4a – 4d shows that a significant relationship between mean weight diameter and organic carbon exists in the 30-50 and 50 - 80 age group as compared to 80-110 and >110 age groups. This indicates that continuous teak growth reduces aggregate stability, hence reduced carbon stability. Earlier studies have indicated that carbon within aggregates is protected physically, chemically or biologically and has longer turnover time than unprotected forms. In other words, the soil organic carbon distribution in soil aggregates controls the sequestration or release of C within a given soil system (Han *et al.* 2010; Sandeep and Manjaiah, 2014). Carbon dynamics in the aggregates is influenced by its recalcitrance and accessibility, and interactions between organic carbon (OC) and soil components (Swanston *et al.,* 2002). Land use and land use changes affect aggregation in a way that the proportion of water stable macroaggregates are reduced under the practices with extensive soil disturbance (Ashagrie *et al,* 2007).

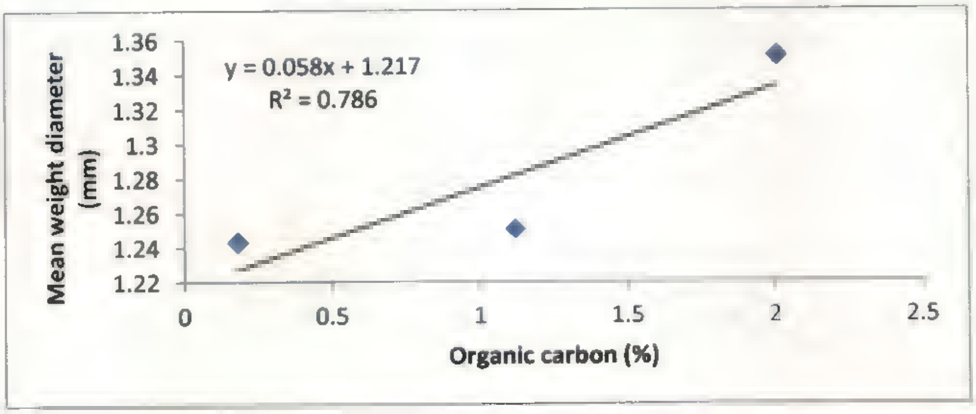

Fig 4a. Relation between organic carbon and mean weight diameter of 30-50 age group plantation

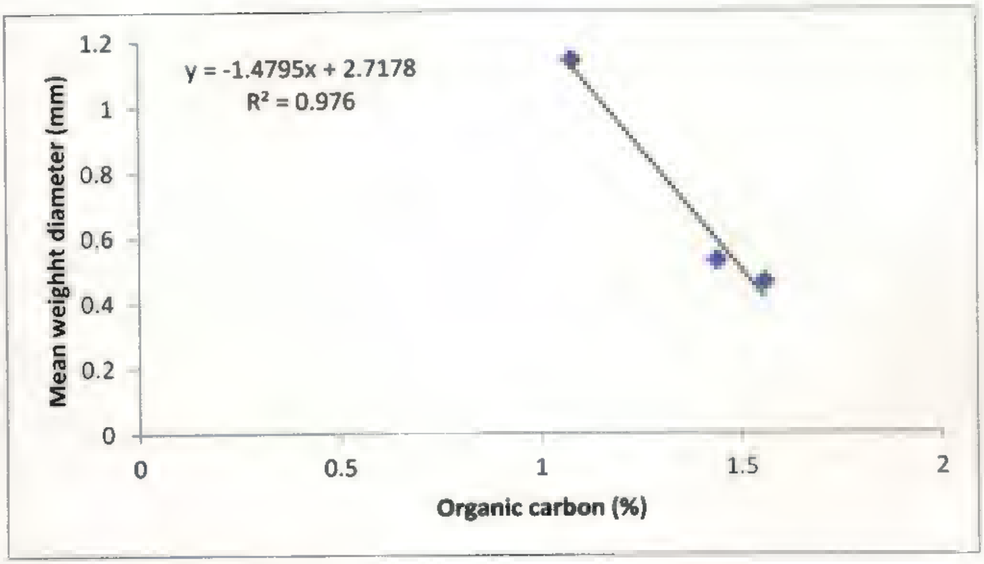

Fig 4b. Relation between organic carbon and mean weight diameter of 50-80 age group plantation

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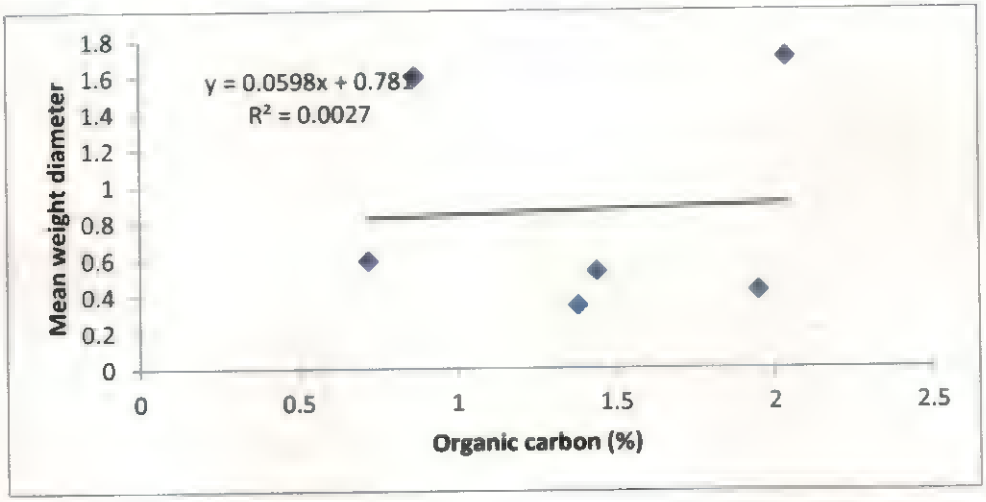

Fig 4c. Relation between organic carbon and mean weight diameter of 80-110 age group plantations

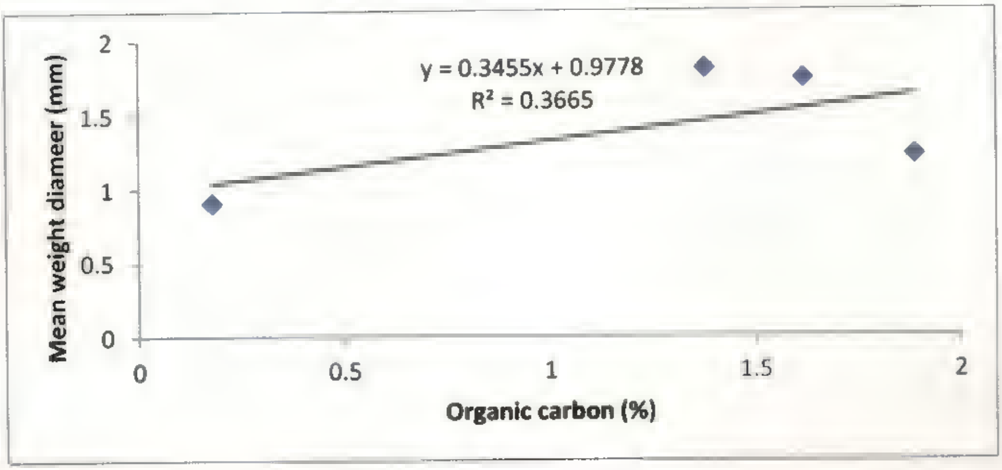

Fig 4d. Relation between organic carbon and mean weight diameter of >110 age group

In soil, no particular trend was found in nitrogen content with period of teak rotations (Fig 5). In Kerala, a common practice in teak at the end of each rotation is to clear fell the area and burn the area to remove the litter remnants. The burning generates a huge heat sufficient to volatize the soil nitrogen leading to its depletion (Certini, 2005). The available P content was found to be depleted in plantation without felling (Fig 6). High P fixation by tropical soils as well as formation of Fe and Al bound P may be the probable reasons for lowering of P content with rotation in teak plantations of Kerala. The other hand, soils with continuous rotation adds P at intervals by way of biomass burning and P addition during the raising of a new rotation. Available potassium content of soil was found to be increasing with each rotation (Fig 7). Tropical soils being rich in illitic mica plays a major role in replenishing the soils with K. The increase in total K content with age could be attributed to the solubilization of K from potassium bearing minerals with age of plantation. Biomass burning at end of each rotation also adds K to soil.

Though teak is a calciphile having a high affinity for Ca, an increase in available Ca content with teak rotations was observed (Fig 8). Ca is an essential element not only from a nutrition point of view but also due to its role in maintains soil health. Calcium helps in soil aggregation and liming soil reaction. Depletion of its stocks will seriously affect soil health. Magnesium on the other hand showed a reverse trend and the soils were found to be enhanced with respect to its contents in plantation without felling year (Fig 9). This increase in Mg creates an imbalance between Ca and Mg in these soils. Improving the Ca additions by way of external input additions may serve as a viable option to sustain soil health in these teak rotations. The analysis of micronutrients Cu, Mn, Zn, Fe and B (Fig 10-14) with long rotation periods and without rotation shows that Mn and Zn decreased substantially whereas there was an enhancement of Fe, B and Cu from first rotation to third roation. While comparing the first rotation plantation with plantation without felling shows that B and Cu contents were increased in other hand there was a decrease in Mn, Zn and Fe contents. Tropical soils are rich in ferromagnesian minerals. The excessive removal of bases and subsequent removal of silica under the basic leachate leads to the accumulation of Fe and Al oxides in the profiles. The results show that continuous teak rotations may lead to laterization and subsequent loss in soil fertility.

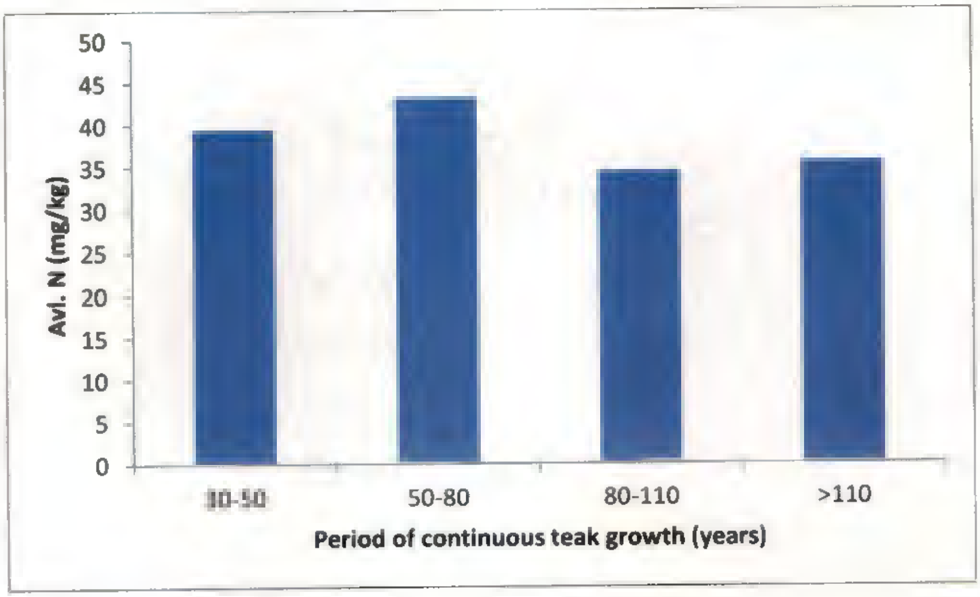

Fig 5. Change in nitrogen content in different age groups

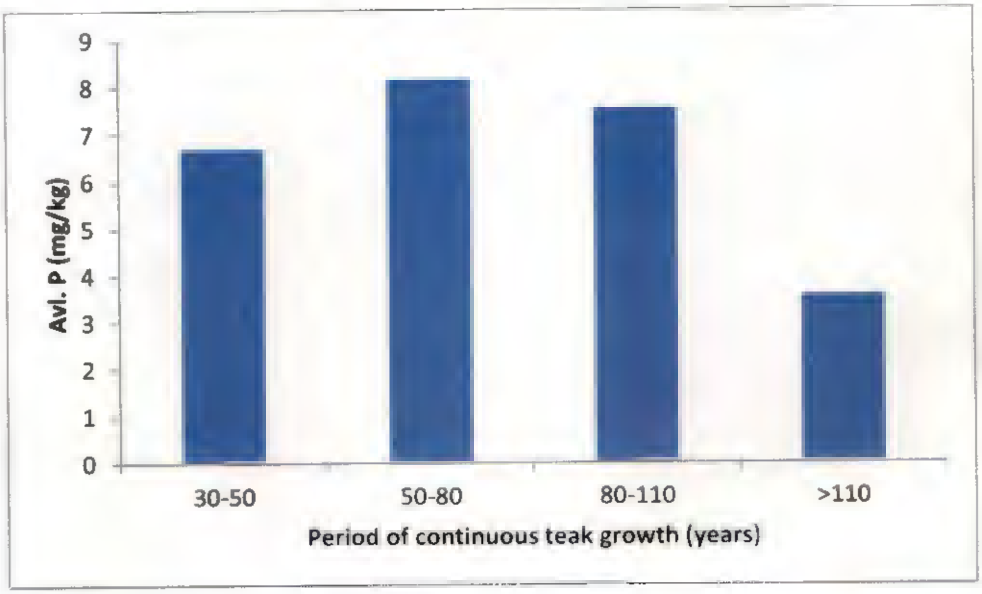

Fig 6. Change in phosphorus content in different age groups

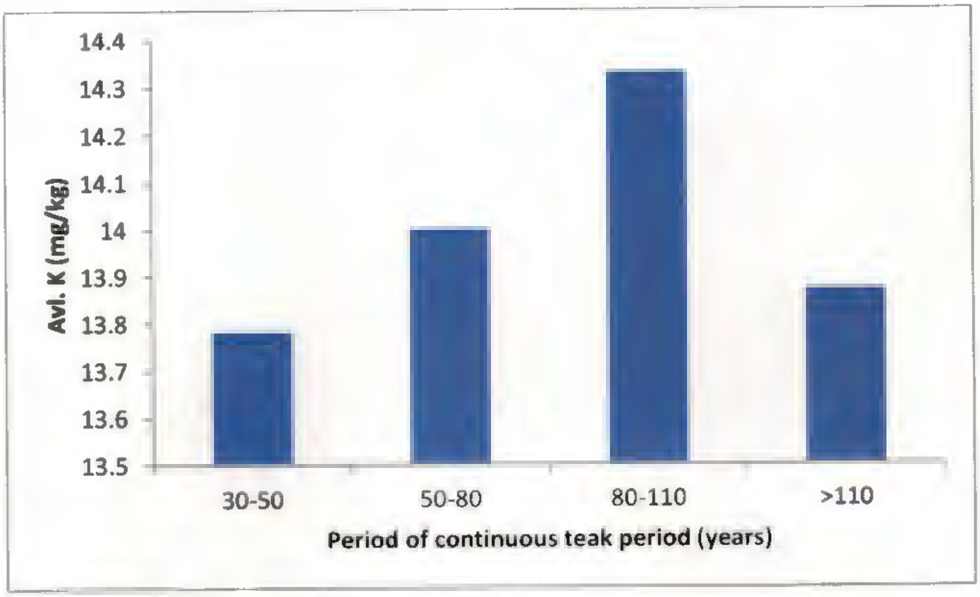

Fig 7. Change in potassium content in different age groups

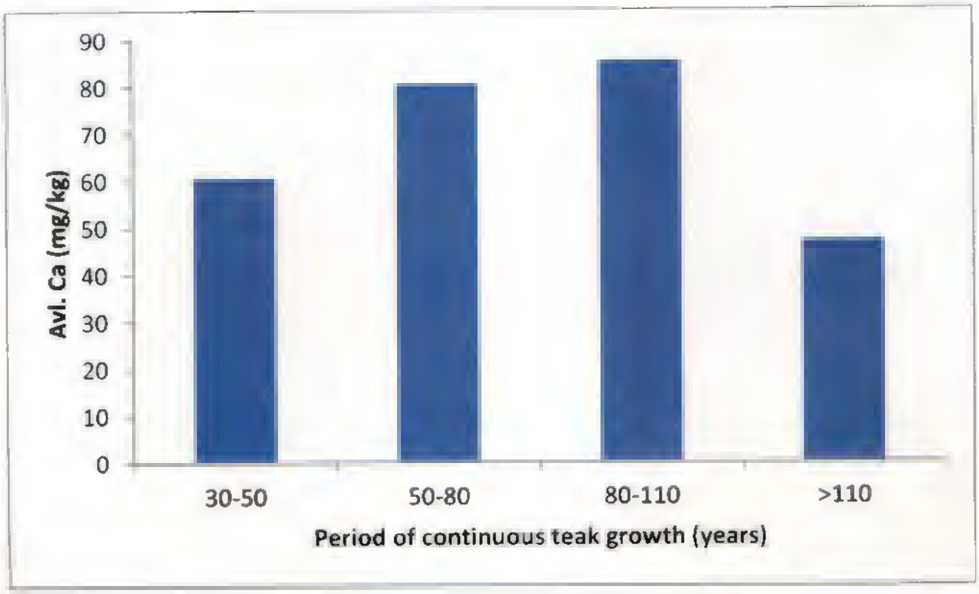

Fig 8. Change in calcium content in different age groups

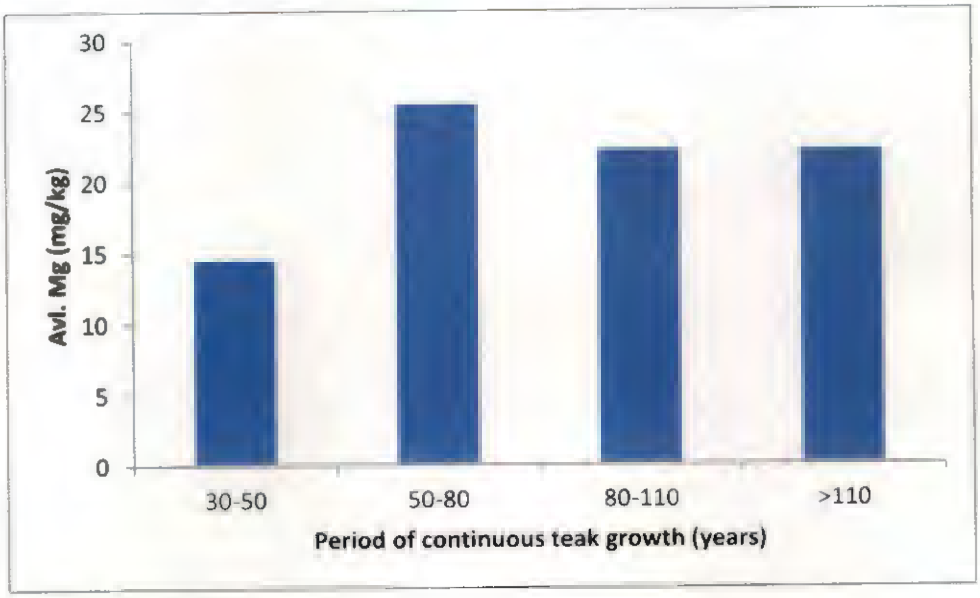

Fig 9. Change in magnesium content in different age groups

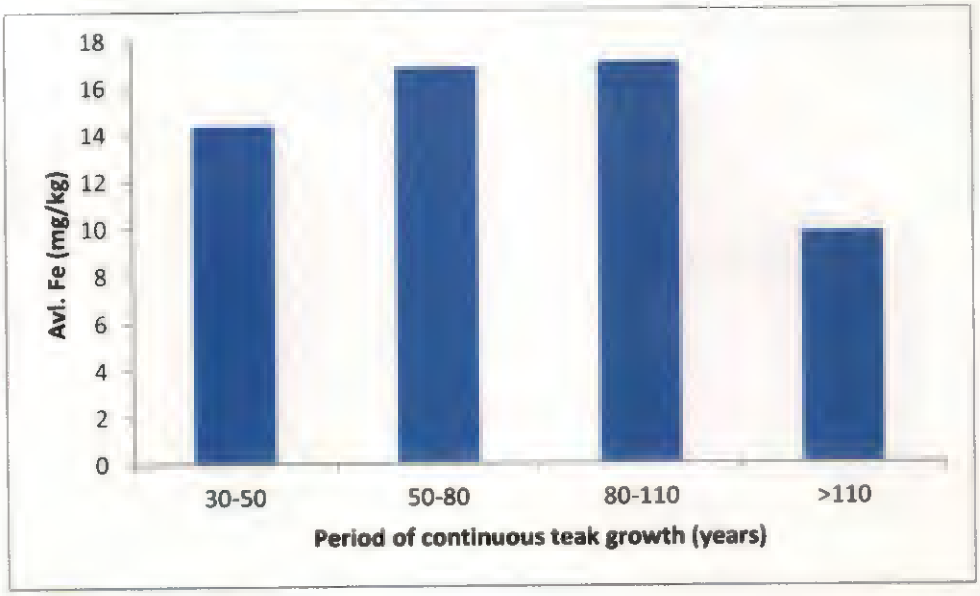

Fig 10. Change in iron content in different age groups

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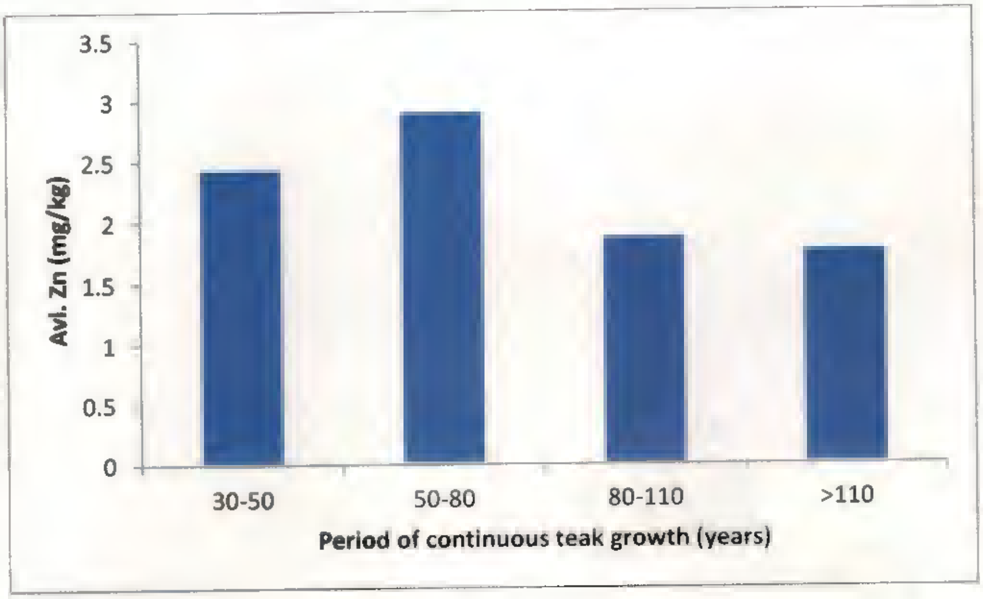

Fig 11. Change in zinc with different age groups

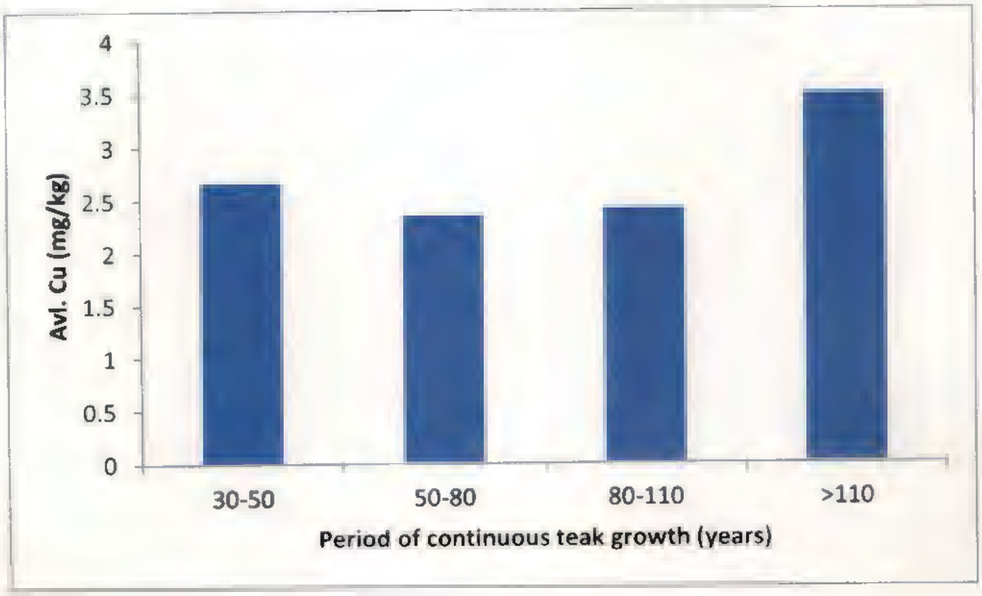

Fig 12. Change in copper content in different age groups

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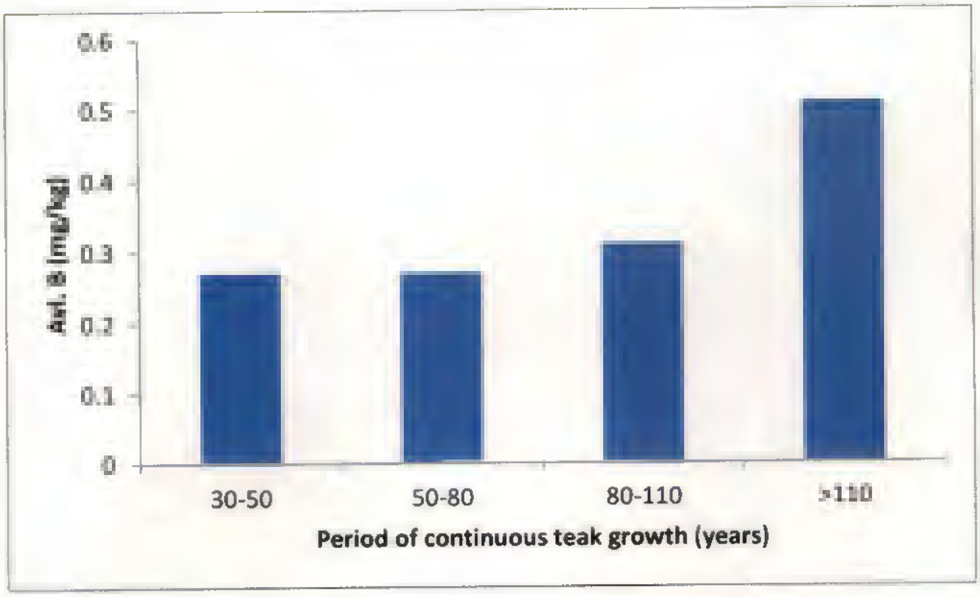

Fig 13. Change in boron content in different age group

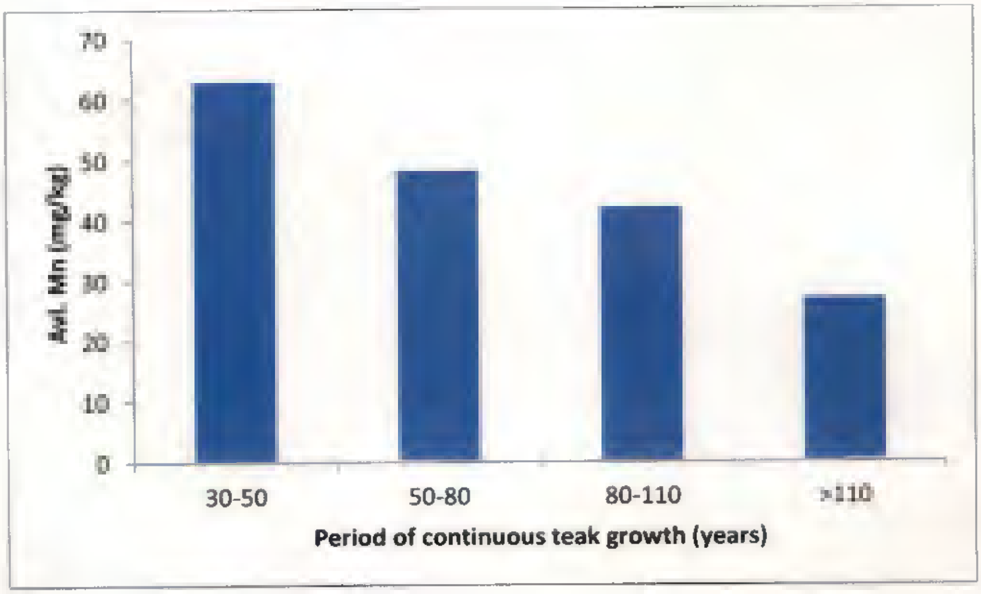

Fig 14. Change in manganese content with different age groups

5.1 CARBON STOCK IN PLANTATIONS

In general, there was no significant difference between the age groups in their carbon storage capacity (Fig 15). This indicates that carbon losses from the teak plantation are readily replenished and the changes may be expected only in the quality of the stored carbon. A slight variation among the carbon stocks between age groups may be on account of site deterioration, variations in quality and quantity of understory vegetation (Champion, 1992, Pandey and Brown, 2000) microbial diversity involved in carbon cycling (Healey and Gara, 2003), fires,and leaf cover (Laurie and Griffith, 1942, Bell, 1973; Balagopalan and Alexander, 1985). After long periods of teak cultivation, the adverse factors affecting soil quality are at a maximum and hence a diverse mix in the quality and complexity of organic matter input to soils detritus originating from leaf, root and mycorrhizal biomass (Hagen-Thorn *et al.*, 2004, Lai *et al.*, 2015, Hobbie *et al.*, 2006, Lynch *et al.*, 2012). The highly complex and heterogeneous organic residues found in the soil organic matter of longer duration plantations along with the lower microbial population prevent maintaining a high level of organic carbon pools in these soils with rotation (Sollins *et al.*, 1996, Sankaran, 1993).

The carbon distribution with depth within the soil profiles in different rotation groups are given in Fig 16. It was found that 70 - 75 percent of the total carbon stocks in the teak plantations of all three rotations are distributed in the 0 - 60 cm depth. The upper 0 - 20 cm layer contains only 35 – 40 percent of the organic carbon. Most of the studies assessing carbon stocks of forest systems considered only the 0 - 30 cm depth for soil carbon stock assessment and this study establishes that calculation of soil carbon stocks up to this depth alone will grossly under represent the actual carbon storage potential of our tropical forest systems. The subsurface layers with active root concentration i.e., 20 – 40cm and 40 - 60 cm together stores approximately 50 per cent of the total stocks.

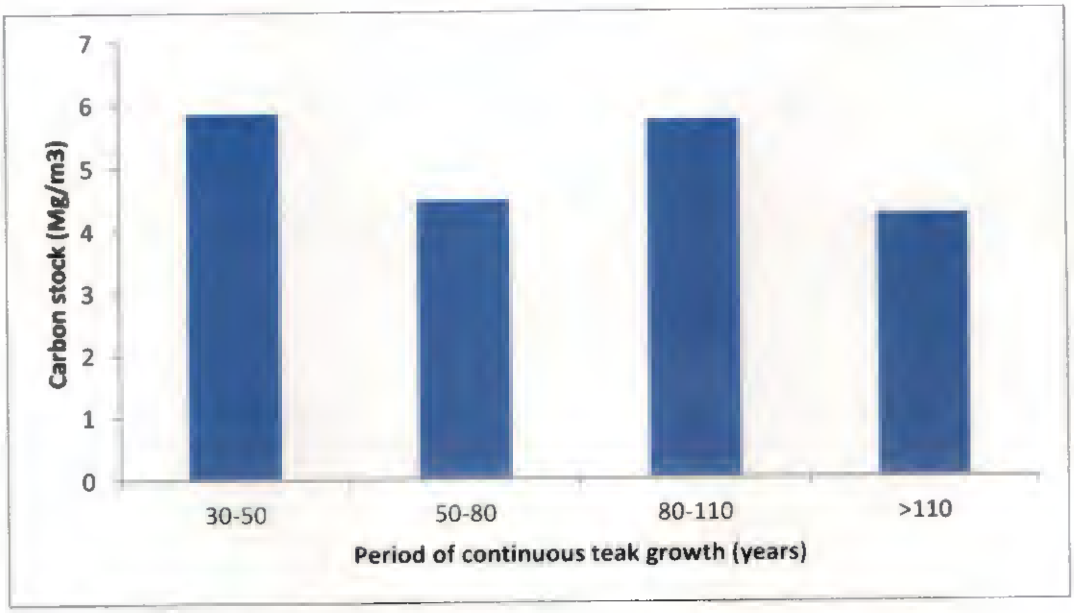

Fig 15. Carbon stock in plantations of different age groups

Under continuous teak growth, macroaggregates were found to store more organic carbon than the microaggregates in respective soils (Fig 17). Free primary particles and silt-sized aggregates (< 20 μm) are bound together into microaggregates (20 – 250 μm) by persistent binding agents (i.e. humified organic matter and polyvalent metal cation complexes), oxides and highly disordered aluminosilicates. These stable microaggregates , in turn, are bound together into macroaggregates (> 250 μm) by temporary (i.e. fungal hyphae and roots) and transient (i.e. microbial- and plant-derived polysaccharides) binding agents (Dexter, 1988). The results in the present study indicate that continuous plant growth leads to a organic matter aided macroagreggate conglomeration in the managed teak plantations of Kerala. The stability of the carbon accumulated therefore was also analyzed in the study and discussed later.

Highest organic carbon content in macroagreggates was found in the surface layers (0 – 20 cm) of plantations without felling (1.22 percent) (Fig 18). Continuous teak rotation was found to gradually increase the organic carbon content in the macroagreggates of surface layers from 0.92 percent in age group 30 – 50 to 1.22 percent in plantations without felling (age group >110). The higher amount of organic carbon in age group >110 indicated reduced occurrence of enzymatic decomposition of carbon in these soils (Puget *et al.*, 1999).

Organic carbon content in both micro- and macroaggregates of surface soils showed an increasing trend with teak rotations further confirming the earlier observation that soil carbon accumulation occurs with period of teak rotation. The results are contray to the earlier observation that continuous cultivation causes a release of carbon by breaking up the aggregate structures, thereby increasing decomposability of carbon. More specifically, cultivation leads to a loss of C-rich macro aggregates and an increase of C-depleted micro aggregates (Elliott, 1986; Six *et al.*, 2000). Unlike agricultural crops, plantations in each age group have relatively longer times for carbon stabilization (20 – 30 years) after temporary disturbances of planting and silvicultural operations.

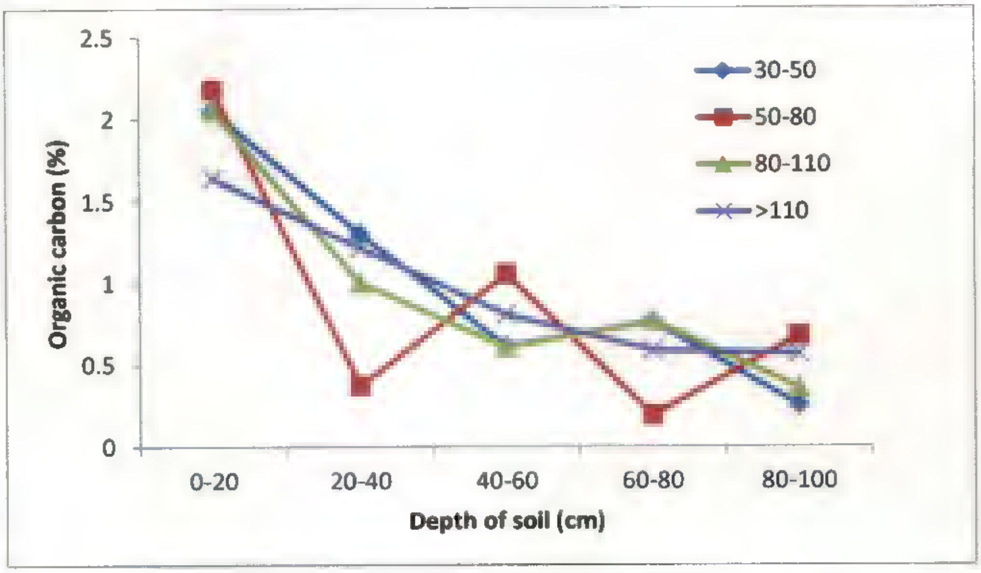

Fig 16. Change in organic carbon with soil depth in teak plantations of different age group

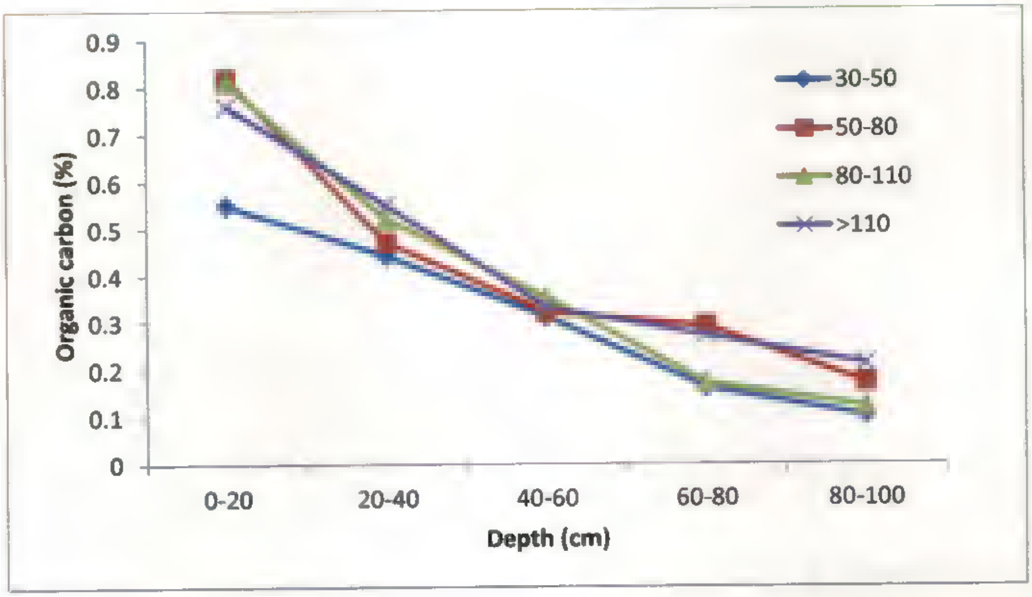

Fig. 17 Change in organic carbon with soil depth in microaggregates

Organic carbon contents in both the aggregate fractions showed a decreasing trend with depth in all age group. Plantations without felling had the maximum content at 80-100 cm and had the minimum variations between depth intervals. This showed that continuous teak growth increasingly translocates higher amounts of carbon to the lower layers and thereby maintains a low variation in carbon distribution between the layers. Carbon mainly translocated to the lower layers by leaching as clay organic complexes (Six *et al.*, 2002). Humid tropics with an intense leaching environment easily promotes such a clay organic movement and accumulation in the lower layers. Plantations like teak with a shallow root depth (0 – 60 cm) fail to recycle the translocated carbon leading to their accumulation.

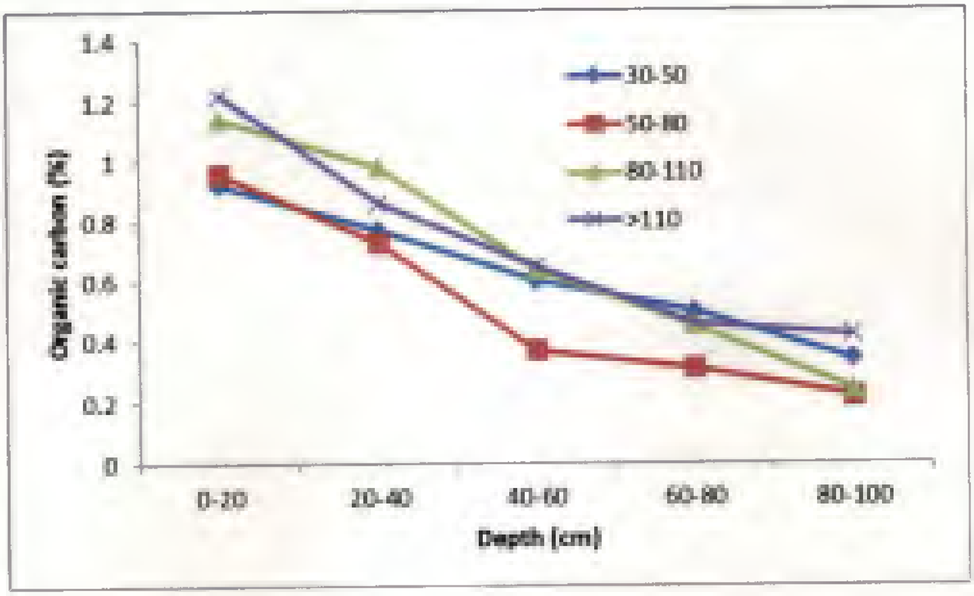

Fig. 18 Change in organic carbon with soil depth in macroaggregates

5.2 CARBON FRACTIONS IN SOIL AND AGGREGATES

Soil carbon fractions in surface soil (0 – 20 cm) are given in Fig 19. Carbon fractions in soil showed a similar trend across age groups. Plantation that was grown continuously showed a relatively lower proportion of active carbon than slow and passive carbon fractions. This indicated that even though there is a total carbon increase in plantations under continuous growth, the entire carbon may not be in a labile form to support ecosystem services (Sandeep *et al.,* 2016). Soil organic carbon includes a complex mix of highly decomposable to very recalcitrant materials, conveniently divided into stabilized and labile fractions. Both these fractions may show different susceptibility to land use and management effects. In cold and/or semiarid region, the carbon stocks in labile particulate SOC fraction constitutes approximately 50 per cent of total soil organic carbon and is the most affected by management practices (Chan 1997). On the other hand, hot and humid environment favors microbial activity that leads to intensive decomposition and humification of labile SOC fractions (Bayer and Bertol 1999). As a result, the reduced carbon pool of these fractions represents a smaller proportion of the total soil organic carbon, compared with more humified

SOC fractions. A similar trend was observed for aggregates as well (Fig. 20 and 21).

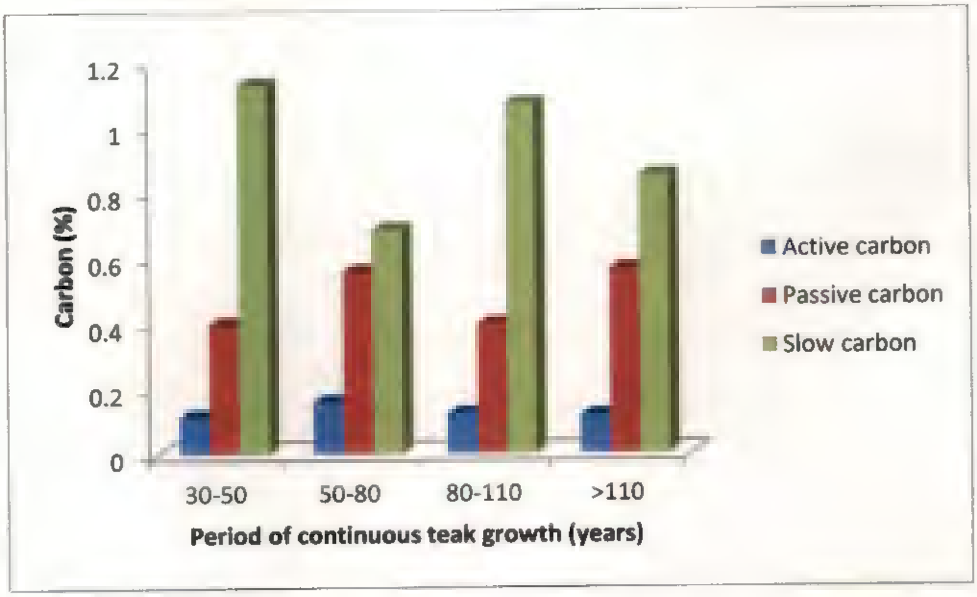

Fig 19 Carbon fractions in soil

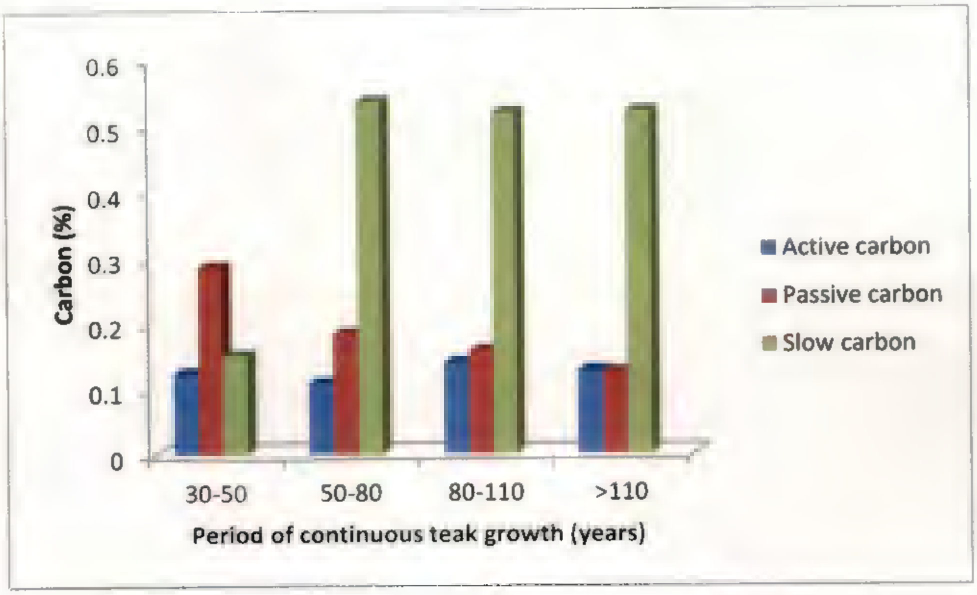

Fig 20. Carbon fractions in microaggregates

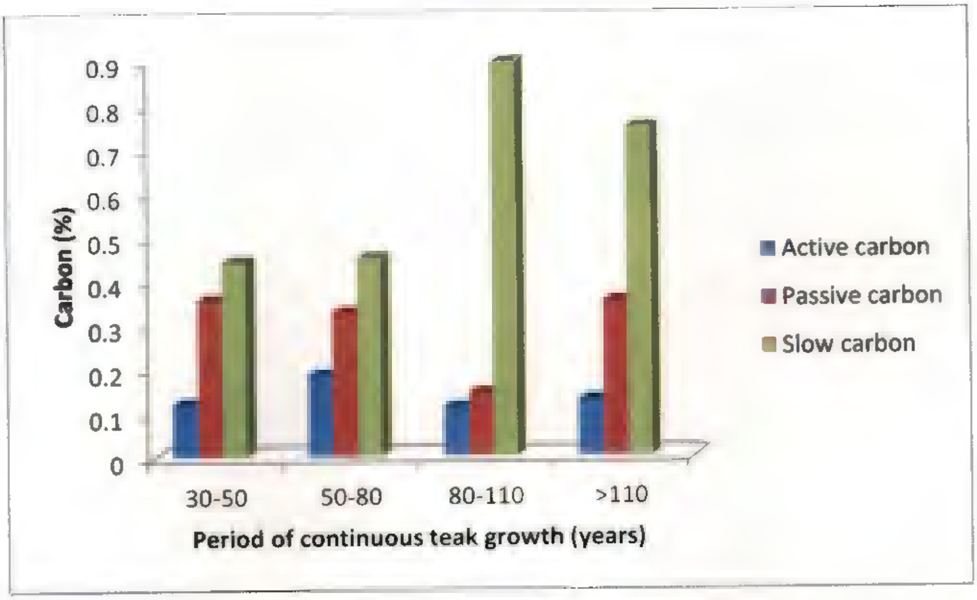

Fig 21. Carbon fractions in macroaggregates

5.3 THERMAL STABILITY OF CARBON IN AGGREGATES

The activation energy and rate constants provide a good insight in to decomposability of organic matter and the pace of mineralization in the soil aggregates (Table 13 and 14). It was observed that micro aggregates provide better protection to organic carbon by a greater complexation mechanism compared to macroaggregates (Six *et al.,* 2002, 2004). In agreement with the earlier studies, in first rotation and plantation grown without felling, the results shows that decomposition rate of carbon stored in micro aggregates, as indicated by reaction rates, were lower than corresponding values for macroaggregates (Table 12). The lower carbon decomposition rates in microaggregates could be attributed to higher level of carbon protection and thereby effective exclusion of microbes and extracellular enzymes (Von Lützow *et al.*, 2006). Further, micro aggregates produces an in situ anaerobic and resulting reducing conditions thereby restricting microbial activity on the carbon substrates (Six *et al.*, 2000). The strong physico – chemical and physical protection offered by microaggregates to organic carbon effectively increases energy of activation (Ea) leading to decreased decomposition rates. In macro aggregates lowest rate of reaction was shown by second and third rotation plantation.

High activation energy ensures that a substantial amount of aggregate organic carbon is protected from decomposition until the requisite energy levels are provided. Activation energy of macroaggregates of plantation grown without felling (51.25 kJ/ mol) showed higher values than other age groups that are rotational plantations indicating that continuous growth of trees increases activation energy of carbon in soil. The activation energy for decomposition of organic carbon in microaggregates ranged from 29.57 to 52.98 kJ/mol and in macroaggregates it ranged between 23.92 to 51.25 kJ/mol. This is in agreement to the earlier reports that micro aggregates provide a better protection for carbon in soil. Micro and macro aggregates from 30-50 age group plantation shows the most vulnerable organic carbon as their activation energy (29.57 kJ/mol and 23.92kJ/mol respectively) were significantly lower than all other age groups. These results indicate that at the start of plantation which involve mainly a conversion from natural forest to plantation, even micro and macro aggregate carbon gets vulnerable to decomposition and takes time for stabilization.

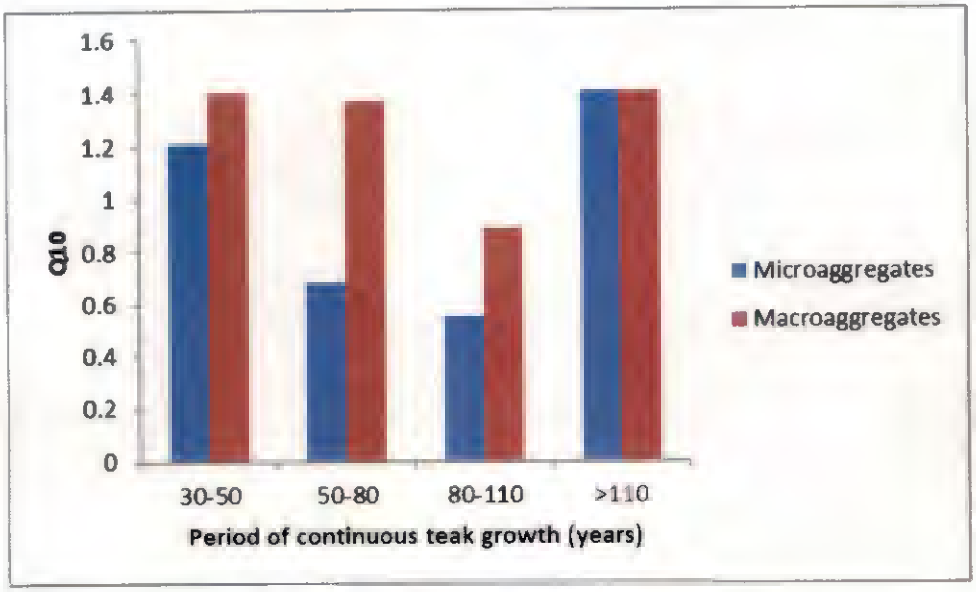

Fig 22. Q_{10} values of macro and microaggregate

Equation 5 depicts that if rate of the reaction is completely temperature independent, the resulting Q_{10} will be 1.0 and the value increases with increasing thermal dependency of the reaction. Here we used Q_{10} as an indicator of temperature dependencies of carbon decomposition in soil aggregates and also to infer the reaction rate changes over a 10°C range of temperature rise (Kirchbaum, 1995). The temperature control on carbon decomposition was found to be more significant in macroaggregates in all age groups, except for third rotation plantation i.e., 80-110 age groups (Fig. 22). By third rotation the aggregate stability and aggregate sizes would have deteriorated on account of the previous clear fellings and subsequent burnings thereby rendering the carbon less dependent on them. Both in microaggregates of second rotation and third rotation plantation, Q_{10} values were found to be around 0.5 indicating lesser temperature dependency of carbon decomposition (Sandeep *et al.,* 2016). Microaggregates show low temperature dependency of carbon than macroaggregates except in plantation grown without felling.

5.4 CARBON DIOXIDE EFFLUX FROM SOIL

Maximum CO_2 evolution was observed in the age group 80 -110 representing third rotation plantations. Moreover, the passive carbon content was found to decrease only to a lesser extent than the first two rotations. In soils there exist a dynamic equilibrium between the three carbon pools – active, slow and passive. Though the degradative forces decompose more of active and slow, passiveness attained by physical means will be in a position to supplement this changes (Parton *et al.,* 1987). The lower depletion of passive carbon in the third rotation indicated that such supplementation doesn't take place in these soils (Fig. 23). Results of the present study indicate that organic carbon has a good correlation with MWD in the first two rotations. Absence of such a correlation in the age group 80 -110 years (third rotation) will essentially leave the organic carbon liable to degradation in these soils. Sandeep and Manjaiah (2014) reported that organic matter enhanced water stable aggregates protect SOC physically by restricting enzyme accessibility, control interactions of food web (Shirani *et al.,* 2002) and consequently reduce carbon mineralization.

The results also showed that more carbon was oxidized at 40°C than at 25°C indicating the release of recalcitrant compounds for enzyme action from the organic materials at higher temperatures (Boddy *et al.*, 2008; Allison *et al.*, 2010). From Fig. 24 it could be observed that the release of carbon for decomposition will be more from the slow pool rather than passive fractions as the latter fraction had no significant change from the initial contents. The results are in confirmation with earlier works (Luo *et al.*, 2001; Allison *et al.*, 2010; Sihi *et al.*, 2016) using microbial enzyme models where microbial acclimatization and increases in microbial biomass and degradative enzyme activity were attributed as key reasons for ephemeral increases in soil respiration with warming.

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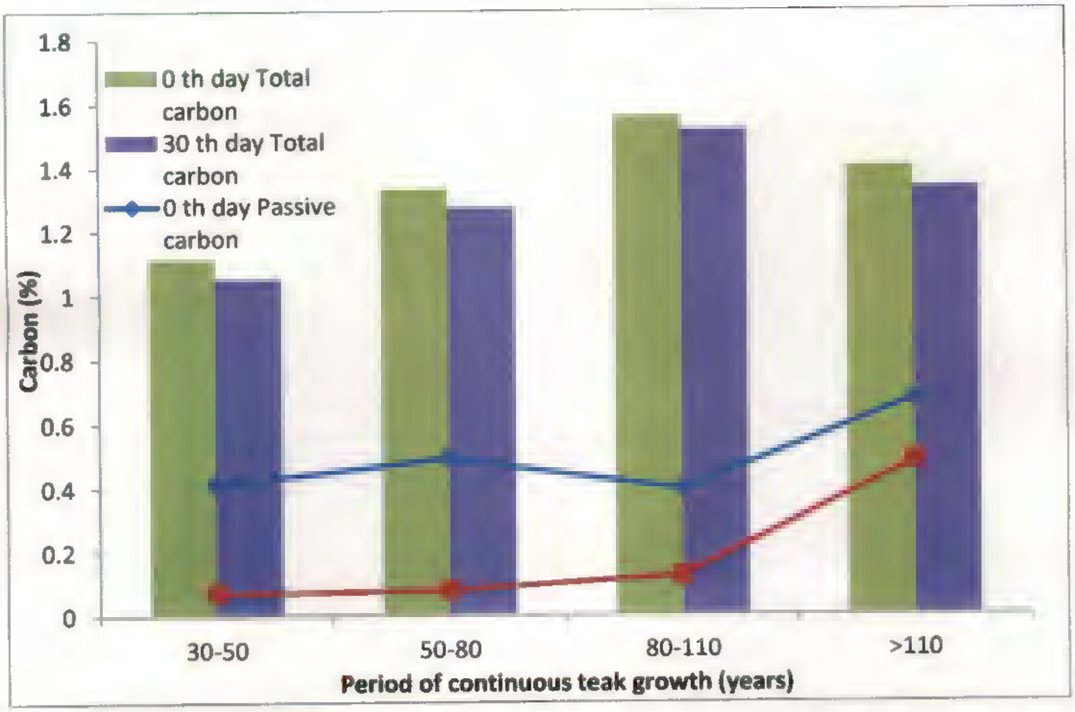

Fig 23. Effect of temperature on passive carbon and total carbon content at 25°c

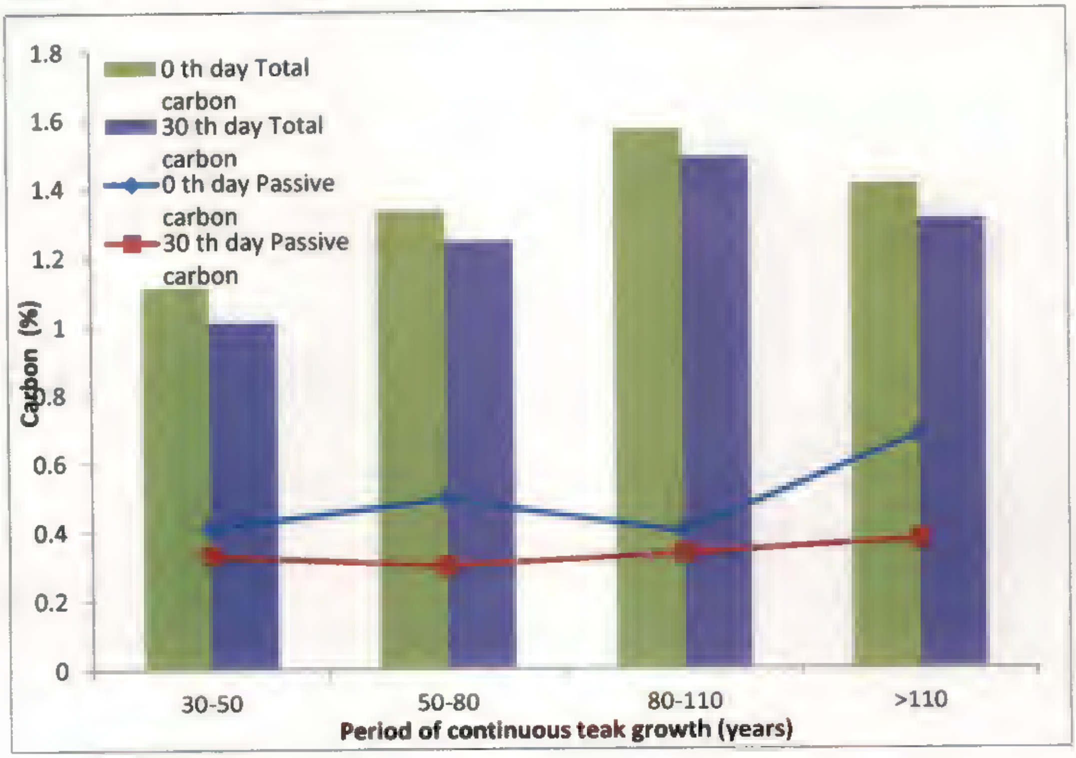

Fig 24. Effect of temperature on passive carbon and total carbon content at 40°c

CHAPTER 6

SUMMARY AND CONCLUSIONS

World soils are an important pool of carbon and play a major role in the global carbon cycle influencing concentration of greenhouse gases in the atmosphere. The present study entitled 'Carbon dynamics in teak planted laterite soils of Kerala' was carried out at Kerala Forest Research Institute, Peechi. The objectives of the study included determination of carbon stocks in managed teak plantations of midland laterites in Kerala, analyzing the thermal stability of carbon decomposition in macro and micro aggregates in these soils and also to study the effects of temperature on carbondioxide efflux from these soils.

Soil samples were collected in a chronosequence from 16 plantations. These plantations were grouped into four age groups of continuous teak growth (30-50, 50-80, 80-110 and >110 years). Basic soil parameters such as pH, electrical conductivity, bulk density, mean weight diameter, texture, nitrogen, potassium, phosphorus, iron, calcium, copper, manganese, magnesium, zinc and boron contents were analyzed using standard protocols. The carbon fractions were assessed with respect to active, slow, passive and total carbon in soil as well as macro and micro. The study also assessed the rate kinetics, thermal stability and cumulative CO_2 efflux of soil carbon decomposition in these soils by batch incubation experiments at different temperatures.

The salient findings are summarized as,

Most predominant soil texture in the teak plantations was sandy loam. The analysis of macronutrients showed that, nitrogen content declined with period of teak rotations whereas potassium content increased with age group. Available P contents depleted in plantations without felling. An imbalance between Ca and Mg in these soils were observed due to increase in Mg in plantations.

The analysis of micronutrients Cu, Mn, Zn Fe and B with long rotation periods and without rotation shows that Mn and Zn decreased substantially

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whereas there was an enhancement of Fe, B and Cu from first rotation to third rotation.

Carbon stock analysis in plantations indicated that carbon losses from the teak plantation are readily replenished and the changes may be expected only in the quality of the stored carbon. It was found that 70 - 75 per cent of the total carbon stocks in the teak plantations of all three rotations are distributed in the 0 - 60 cm depth. The upper 0 - 30 cm layer contained only 35 – 40 per cent of the organic carbon, hence using this depth for stock estimations would be a gross under representation of the actual carbon storage potential of these plantations.

While analyzing the carbon stored in aggregates, results indicated that under continuous teak growth, macroaggregates were found to store more organic carbon than the microaggregates in respective soils. This indicated that continuous plant growth leads to an organic matter aided macroagreggate conglomeration in the managed teak plantations of Kerala. More specifically, continuous teak rotation leads to a loss of C-rich macro aggregates and an increase of C-depleted micro aggregates in these managed forest systems.

Analysis of organic carbon contents in both the aggregate fractions (macro and micro) showed a decreasing trend with depth in all age groups. Plantations without felling had the maximum content at 80-100cm and had the minimum variations between depth intervals. This showed that continuous teak growth increasingly translocates higher amounts of carbon to the lower layers and thereby maintains a low variation in carbon distribution between the layers. Carbon fraction analysis showed that plantations that were grown continuously without felling have a relatively lower proportion of active carbon than slow and passive carbon fractions. This indicated that even though there is a total carbon increase in plantations under continuous growth, the entire carbon may not be in a labile form to support ecosystem services.

Activation energy of macroaggregates of plantation grown without felling (48.23 kJ/mol) showed higher values than other age groups that are under rotation plantations indicating that continuous growth of trees along with a stress free environment increases activation energy of carbon in soil. Q_{10} analysis of soil carbon indicates that the temperature control on carbon decomposition was found to be more significant in macroaggregates in all age groups, except for third rotation plantation. Both in microaggregates of second rotation and third rotation plantation, Q_{10} values were found to be around 0.5 indicating lesser temperature dependency of carbon decomposition. Microaggregates showed low temperature dependency of carbon than macroaggregates except in plantation without felling.

Maximum CO_2 evolution was observed in the age group 80 -110 years representing third rotation plantations. Moreover, the passive carbon content was found to decrease only to a lesser extend than the first two rotations. The lower depletion of passive carbon in the third rotation indicates that there is no supplementation of passive carbon to active and slow pool in these soils and the former fraction is relatively inert to decomposition. Carbon pool analysis at different temperature indicated that more carbon was oxidized at 40°C than 25°C indicating the release of even recalcitrant compounds for enzyme action from the organic materials at higher temperature. This in turn exposes the potential of these plantations to revert to a carbon source rather than sink under predicted global warming scenarios.

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CARBON DYNAMICS IN TEAK PLANTED LATERITE SOILS OF KERALA

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ABSTRACT OF THE THESIS

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ABSTRACT

Global warming due to increased concentration of greenhouse gases (GHGs) is one of the important concerns of mankind today. The global soils store about 2500 Gt of carbon which is approximately 3.3 times the atmospheric carbon pool (760 Gt) and 4.5 times than that of the biotic pool (560 Gt) . Kerala has a rich forest cover of which 10 per cent is occupied by forest plantations. Among the plantation species, teak occupies the most prominent position both in acceptance and coverage. However, continuous teak rotation affects the quantity and stability. Hence the present study was taken up to assess the changes in carbon fractions and carbon stability under continuous teak rotations in midland laterites of Kerala.

Soils were collected to a depth of 1 m with a depth interval of 20 cm in a chronosequence from 16 plantations at Nilambur, Kerala. Basic soil parameters such as pH, electrical conductivity, bulk density, mean weight diameter, texture, available nitrogen, potassium, phosphorus, iron, calcium, copper, manganese, magnesium, zinc and boron content were analyzed using standard protocols. The carbon fractions were assessed with respect to active, slow, passive and total carbon in soil as well as macro and micro aggregates. The study also assessed the rate kinetics, thermal stability and cumulative CO_2 efflux of soil carbon decomposition in these soils by batch incubation experiments at different temperatures.

The results showed a reduction of soil basic characters below critical levels with continuous teak rotations. In general, the carbon content was found to decrease depth wise with rotation. However, in plantations without felling organic carbon was found distributed equally in all the layers which may be due to the unhindered transportation and translocation of humic materials with time in these plantations. The carbon stocks in the plantations do not have significant difference between the age groups in their carbon storage capacity. This

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indicated that carbon losses from the teak plantation are readily replenished and the changes may be expected only in the quality of the stored carbon. Macroaggregates were found to store more organic carbon than the microaggregates. The correlation between carbon and aggregate stability was found to decrease with rotation. Plantation that was grown continuously showed a relatively lower proportion of active carbon than slow and passive carbon fractions. This indicated that even though there was a total carbon increase in plantations under continuous growth, the entire carbon may not be in a labile form to support ecosystem services.

Thermal stability studies showed that microaggregates provided better protection to organic carbon by a greater complex mechanism compared to macroaggregates. With temperature, there was an increased conversion of active carbon to passive forms and this conversion could lead to higher carbondioxide evolution once the threshold energy levels were attained. Carbon dioxide efflux studies confirmed these results as higher cumulative CO_2 evolution was obtained at 40°C than 25°C in all soils. Further, cumulative CO_2 evolution from continuous plantation without felling didn't get affected with temperature indicating a dynamic equilibrium with atmosphere. The present study concluded that continuous teak rotation destabilizes carbon in soil and shows the potential to revert to a carbon source than sink if not managed sustainably.